THE CONSTITUTION OF MATTER

JOSEPH S. AMES

Northwestern University

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BY

JOSEPH S. AMES, Ph.D.

PROFESSOR OF PHYSICS

AND DIRECTOR OF THE PHYSICAL LABORATORY

JOHNS HOPKINS UNIVERSITY

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PREFACE

The lectures which form the body of this book were delivered at Northwestern University, Evanston, Illinois, in the month of February, 1913, for The Norman W. Harris Lectures of this year. The fact that they were actual lectures accounts for the form in which the text is given; and the further fact that the audience for whom they were prepared was composed, for a large part, of people unfamiliar with both the facts and the methods of science must be accepted as the justification for the treatment of the subject.

Few tasks are as difficult as that of conveying to a general audience a true impression of the results of scientific inquiry. One must avoid the Scylla of too great certainty and also the Charybdis of too great uncertainty. Even the proper words to use are a matter of doubt; and the difficulty is not lightened by the fact that, through the daily press and the

popular magazines, many of the discoveries of science have been given exposition — in many cases, by people entirely ignorant of the subject.

The plan adopted, after most serious consideration, was to accept the general theory of molecules and atoms as proposed by Sir J. J. Thomson and the properties of electrons as deduced by H. A. Lorentz, and to attempt to explain how from these one may deduce the general and even specific properties of matter. This method obviously is one suited only for a general audience; and even there it has its dangers. One is liable to produce the impression that our theories are verified, whereas they are but hypotheses still; but this is better, perhaps, than to leave the conviction that nothing is certain. It is difficult to make any body of listeners, however great their general intelligence, realize that in the end the great purpose of scientific investigation is the pursuit of Truth, the attainment of knowledge. Hypotheses rise and fall; the facts of experiment remain.

The temptation is great to stop here and there and emphasize what is not known, what is not proved; and the real usefulness of the lectures is lessened of course by the fact that this was done so rarely. However successful the attempt has been, the main purpose of the lectures was to make clear to a body of people, not students of physics, some of the results of investigators in unifying our knowledge of the world around us.

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I

GENERAL PROPERTIES OF MATTER; MASS

In beginning a course of lectures upon any subject connected with physical science, it is necessary to devote some time to fundamental ideas and definitions. This is specially true in dealing with the "Constitution of Matter," the subject of this course, involving as it does knowledge of the subjects of heat, light, and electricity in addition to that of the familiar properties of matter.

We must understand what is meant by the word "matter"; we must describe its properties as revealed by experiments; and then we shall be ready to discuss the theories which aim to correlate these properties.

The method which has been followed in the study of this particular problem is the same as is used in any investigation in science; and,

although it may be clear to the larger part of this audience, it is of such importance that I must call your attention to its essential steps.

All of us have certain sense-organs which, when stimulated, give rise to definite sensations: these have been called our "gates to knowledge." It is thus that we first learn about the world of nature around us. The process is very slow, as any one knows who has observed a child striving to connect its sensations of sight and touch, and noted how slowly it learns to trace a contour with its finger. At first we attribute the cause of our various sensations to certain definite geometrical figures: thus we can see a stone or a block of wood; if we put our fingers on it, we can trace its surface; if we hold it in our hands we are conscious of a pressure, etc. We predicate the *existence* of something occupying this figure, bounded by this surface, and call it "matter." The fact that, when we hold a stone in our hands, we experience a pressure is said to be due to a "property" of matter. By means of our various senses we learn to attribute

many properties to the stone or the block of wood; and the early history of science is simply an enumeration of these properties. We perform simple experiments ourselves every day we live, and we soon learn to believe that, if we can repeat identically any given set of conditions, the same event will follow, regardless of the time or place. Such a belief is in reality the first great principle of science. Through our senses also we observe phenomena which occur at a distance from ourselves, such as the motions of the planets, the flashes of lightning, all of which go to make complete our mental picture of nature.

It was very soon evident in the progress of science that many phenomena, many properties of matter, were connected; so that, granting one, another would follow as a logical consequence; and the recognition of this fact was a most important step. Thus, Newton showed that the tidal motion of the oceans, the revolution of the moon around the earth, and the apple falling from its tree were all illustrations of one and the same principle. Similarly, all

investigators in the field of science, all philosophers, are seeking to prove the interdependence of natural phenomena of every kind. Each year sees us able to reduce in number the statements required to describe these; and when we say "we explain" one, all that is meant is that we are able to show that it follows logically from our previous knowledge.

Before, however, we can speak of knowledge of a phenomenon, we must be able to describe it in precise language. Thus, we observe that all bodies heavier than air fall towards the earth if they are free to drop; further, we observe that all bodies, a feather or a leaden bullet, will fall side by side in a space from which the air has been exhausted by an air-pump; but our knowledge of falling bodies is not complete until we know the time required by a body to fall through any known portion of its path; we must be able to give numbers to each element of the motion. Here is where a difficulty enters: what features of a phenomenon shall we regard as elementary? That is, what features are so simple that they do not

admit explanation in simpler language? We may begin by assuming, as did Newton, that our idea of duration of time and of space extension, such as length, area, and volume, are intuitive and that our ordinary methods of giving numbers by clocks and rules are satisfactory; but which properties of matter shall we choose as fundamental? and in case the phenomenon is one involving electrical, magnetic, thermal, luminous, or other effects, what steps shall we take? The progress of science has been most gradual. At first as many of the ideas were considered elementary as was thought convenient, provided only that numerical values could be given them; then, in course of time, by a process of making hypotheses and testing them by further experiments and observations, it was proved that some of these preliminary elementary quantities were connected; so that at the present time there are required for the expression of our description of natural phenomena comparatively few quantities. What these are will appear in the course of these lectures.

Let me repeat in a summary the essentials of what has been called "the scientific method." A phenomenon is observed through our senses; we investigate the conditions under which it occurs; we give numerical values to all the quantities concerned so as to describe it in mathematical language; then, by a comparison of this with other phenomena, we attempt to discover some few simple mathematical statements which, if true, involve as logical consequences those describing all the observations made. These simple statements are called the "laws of nature"; and the quantities involved in them are called the "fundamental quantities" of matter. It must be remembered that these last may deserve their name "fundamental" for a brief season only; because, as observations continue, we may find that two or more of them are so related that they may be expressed in terms of the same quantity.

Each of our senses introduces us to a certain set of phenomena; and in many cases we can by proper means include these in organized science. Thus, we have a temperature-sense

by means of which we recognize that bodies differ in "hotness"; some we call "hot," others "cold." By means of our senses alone we can do little more than this; but if we subject a piece of ordinary matter to the conditions to which we give the names hot or cold, e.g., hold it near a flame, or put it on a block of ice, we may observe that many of its properties, such as its size, change; these changes we can measure. Further, we can determine the exact conditions which cause the states we call hot or cold; and thus a field of scientific investigation is opened.

Another sense which we all have is one called the "muscle-sense"; by it we are conscious of exerting a force, producing an effort. It may be stimulated in various ways. Thus, if one stops or throws a ball, there is a definite sensation, or, in fact, if we alter the motion of any body. By means of our senses alone we cannot give a number to the sensation; but we can recognize differences in its intensity. If the same body is given in turn first a great velocity and then a less one, the sensation in

the former case is more intense; or, if two different bodies are given the same speed, e.g., a tennis-ball and a baseball, the sensation in the latter case is the more intense; i.e., for a given change in motion intensity of sensation is associated with a dense body. There is thus a property of matter which becomes apparent to our muscle-sense when the velocity of a body is changed; and in this connection we speak of its "inertia." The proper numerical value to be attached to this will be discussed shortly.

Again, if one holds a body in the hand or supports a load on the back, one is conscious of a definite sensation through the muscle-sense; and again there are differences in the sensation depending upon the nature of the load; a box full of sand produces a more intense sensation than the same box would if empty. Thus we speak of a body as being "heavy" or "light." Here we have another property of matter, called its "weight," which at first sight has no connection with the previous one, inasmuch as this property depends upon the presence of the earth.

Again, if a rod held in the hands is twisted or bent, the same muscle-sense is stimulated, and by means of it certain definite properties of matter may be investigated, such as "elasticity," "ductility," etc.

These properties of matter form the basis of the science called mechanics; and each must be studied in detail, for any theory of the constitution of matter must have in it the possibility of explaining these properties, as well as others to be described presently.

In order to study these properties of matter, some method must be devised for their investigation which is independent of our muscle-senses; these last simply call attention to the phenomena and note differences in intensity; by means of them we could never assign numerical quantities. We can tell fairly well if one body has the same weight as another; but there is no certainty in our minds as to exact equality. One simple way of securing by external means the effects which I have described in connection with our muscles is to use a spiral coiled spring: if such a spring is com-

pressed and then allowed to expand, it will give velocity to a ball, as in a toy gun; if a body is placed on top of such a spring, it will be compressed and finally come to rest supporting the body; by means of compressed springs we may easily imagine a body distorted and bent. The use of a compressed spring is not, however, a particularly simple phenomenon; for its effect depends upon the material of the spring, its temperature, etc.; and further we cannot see what is going on inside the material of the spring.

If we demand the simplest way in which the motion of a body may be changed, it will be seen to be by allowing another body to impinge on it; this is illustrated by the game of billiards, provided we assume that the table itself is horizontal and has no action on the velocity. Here we have the exceedingly elementary idea of two bodies, having definite motions, impinging, and then having different motions; the motion of each body is altered by the action of the other. This particular phenomenon was studied by Wallis, Sir Chris-

topher Wren, Christian Huyghens, and Sir Isaac Newton, at about the same time. Their method was to suspend two heavy bodies, such as two lead or ivory balls, hanging them from long threads of the same length; to draw the bodies sidewise, release them, and allow them to impinge when both were at their lowest points; and to observe the velocities before and after impact. This measurement of velocity is not difficult, because, as Galileo was the first to prove, if a body is swinging like a pendulum under the action of gravity, its velocity at the lowest point of its swing is proportional to the chord of the arc of the circle through which it has fallen, and, if such a suspended body is given a certain sidewise velocity when it is hanging at rest, it will rise through an arc, the chord of which is proportional to this velocity.

The important conclusion drawn by Newton from these observations was that using the *same two bodies, the ratio of their changes in velocity due to impact is always the same,* regardless of the length of the suspending

threads or the arcs through which they fall. (Of course, in calculating the change in velocity the observers were careful to measure the velocities of motion always in the same direction, e.g., towards the right; so, if it is said that a velocity is increased, it is meant that the velocity towards the right is increased, etc.) If the two bodies are of the same material, e.g., both made of ivory, the larger one has the less change in its motion; and the same is true in all cases of the body which has in it what we may call the greater "quantity of matter." It was noted, further, that these changes in velocity were always opposite in direction for the two bodies; i.e., using most general language, if one body is given a push to the right as the result of the impact, the other receives a push to the left.

The fact of the constancy of this ratio of the velocity-changes enables us to give a number to each body, which is characteristic of its inertia. Let me remind you of how we give a number to the length of a table: we select arbitrarily a certain rod, and call its

length any number we choose, thus we give the number *three* to a yardstick,—and then by a method of superposition we ascertain how many times the length of this rod is contained in that of the table. So here in the case of these impact experiments, let us call the change in the velocity of one body by the symbol c_1, and that in the velocity of the other, c_2, and, remembering that their ratio $\frac{c_1}{c_2}$ is always the same for the same two bodies, we can give arbitrarily a number, m_1, to the first body and then *define* the corresponding number for the second body to be given by a number, m_2, such that

$$m_2 = m_1 \frac{c_1}{c_2}$$

This gives us, then, a definite number for the second body. Let us see what property of the body this number measures. It is evident from the definition that, if the change in the motion of the second body is small, the value of m is large, and *vice versa;* so that the size of m corresponds to the opposition offered by the

body to having its motion changed; this property is what we think of when we speak of the "quantity of matter" in a body, and it was called by Newton its "mass."

In a similar manner, by suspending a third body in place of the second, and using the same number m_1 for the first body, we may obtain a number m_3 for the mass of this, etc. Newton convinced himself that this mode of assigning numbers to the mass of a body was perfectly consistent; and we adopt it as our definition of "mass."

We can get more familiar illustrations of this idea of mass if we consider other cases of the interaction of two bodies. Thus, if a man standing on a board which rests on smooth ice jumps sidewise, the board will be pushed in the opposite direction; and, if the man has a greater mass than the board, his velocity will be less. When a bullet is expelled from a gun, there is a recoil of the latter; and, owing to the small mass of the bullet, its velocity is great. (In both these last cases it should be noted that, since the motion begins from rest,

the *change* in the velocity becomes the velocity resulting from the interaction of the bodies.)

It is evident, then, that the mass of a body is a real property of that body, just as much so as its shape, size, or color. We do not recognize it by our senses of sight, or touch, or taste; but it is apparent to us through our muscle-sense when we change the motion of the body. The genius of Newton was never shown more clearly than in his conception of this fundamental property of matter and in his introduction of it into the expression or description of natural phenomena.

It is obvious, of course, that the exact *number* assigned to the mass of any body depends upon the choice of a standard body of reference and the number given it; but, if the latter is changed, or if different nations adopt different standards, the only effect is to change in the same ratio the numbers given the masses of all bodies. The English-speaking people express mass in terms of "pounds"; while the scientific unit is the "gram."

We have used for purposes of definition

an impact experiment, which is applicable only to solid bodies, but other methods for determining the values of mass have been devised, which can be used for all kinds of bodies, solids, liquids, or gases.

When accurate methods of measurement are used, a most important fact is discovered; namely, the mass of a body is definitely characteristic of it; it cannot be changed. We can easily alter its shape, size, color, etc., e.g., by raising its temperature or by twisting it; but the mass remains unaffected. If a block of ice melts, or if the resulting water is changed into steam, we believe that there is no change in the mass. If a body is broken into fragments; or if two or more bodies unite to form one, the mass of the whole is found to equal the sum of the masses of the parts. This general statement is called the principle of the "conservation of matter."

In the course of these lectures it will be shown that there are other things in nature than material bodies — as we use these words ordinarily — which possess mass; and in the

complete statement of all laws referring to mass, these must be included. As a matter of fact, however, this additional mass does not enter into our ordinary experience.

Returning for a moment to the impact experiment, we can easily see that there is another mode of description, which is perhaps more easily remembered. The numbers assigned the masses of the two bodies were so selected as to be inversely proportional to the changes in the velocity; that is, using the same symbols as before, —

$$\frac{m_2}{m_1} = \frac{c_1}{c_2}$$

or $m_1c_1 = m_2c_2$ numerically.

But the changes in velocity are *opposite* in direction; if one is an increase, the other is a decrease; so we may state all the facts by writing

$$m_1c_1 = -m_2c_2$$

The product of mass by velocity is called "momentum"; thus m_1c_1 is the change in momentum of the first body, and m_2c_2 is that of the second. Hence we see that the increase

of momentum of one body is equal to the decrease of momentum of the other; which is equivalent to saying that the total momentum of the two does not change during the impact.

This idea of momentum is of fundamental importance in our concept of mass. Our first approach to it comes through an experiment consisting in stopping a moving body, and the intensity of the sensation, depending, as it does, upon both the body and its velocity, really measures its momentum. We must note further, that when we say that a body has a definite velocity, we mean that it is moving in a definite direction with a definite speed; and therefore, if we have a collection of bodies moving in different directions, their effective momentum in any one direction can be found from the momenta of the separate bodies only by making allowance for the directions of motion. Thus a bullet striking a target obliquely does not impart as great a blow as if it had struck it perpendicularly.

The substance of what I have said thus far about mass is this: there is a definite property

of matter, called its mass, of which we become conscious through our muscle-sense; but the intensity of the sensation depends upon the change produced in the momentum, that is the product of mass and velocity.[1]

The change in motion of which we have spoken in these impact experiments of Newton is, of course, the total change between the two instants when impact begins and when it ends; the change goes on during the interval between these, but it is difficult to observe the change for any portion of it. In other cases of change of motion, however, this is distributed over a sufficient interval of time for one to study it more in detail. At any given instant the motion is changing at a definite rate per unit of time; this is called the "acceleration." Newton formulated certain hypotheses in regard to changes of motion in bodies, which he showed were actually

[1] Galileo perceived clearly that in all impact or similar experiments the effects produced depended upon two properties of the body concerned; one, internal, the same always for the same body; the other external, conditioned by its velocity.

verified so far as observation permitted him to say. These may be stated as follows:—

(1) Whenever the motion of a body changes, it is owing to what we may call the "action" of another body; i.e., the motion of a body left to itself would never change. (This idea was also held by Galileo, many years before Newton.)

(2) When two bodies which are free to move do act on each other, the motion of each is changed and in such a manner that calling a_1 and a_2 the accelerations at any instant, and m_1 and m_2 the masses, a_1 and a_2 are in opposite directions, and numerically $\frac{a_2}{a_1} = \frac{m_1}{m_2}$. That is, m_1a_1 equals m_2a_2 numerically, but is opposite in direction: "Action and reaction are equal and opposite." (The particular point of the body whose acceleration is indicated by a is what is called the "center of mass." It is easily determined by experiment or by calculation; e.g., it is the center of a uniform sphere, the middle point of a uniform rod, etc.)

(3) If three or more bodies are interacting simultaneously, each simple action between any two bodies is the same as if the other bodies were not present; and the total acceleration of any one body is the combined result of the separate actions of all the other bodies.

Therefore, calling a the acceleration at any instant of a body whose mass is m, the product ma is in every sense a proper measure of the external agencies acting on it at that instant. If there is no acceleration, it does not imply that there are no external agencies, but that, if there are any, their actions neutralize each other.

In describing changes of motion of bodies, Newton introduced a form of words which has proved to be most convenient. Whenever a set of conditions exists under which a body experiences an acceleration, we say "a force is acting on the body"; and the product of the numerical values of the mass of the body and of its acceleration is taken as the numerical value of the force. Thus, we speak of the

"force of gravity," meaning that, if a body is released so as to be free to move, it will have an acceleration towards the earth; we speak of the force due to the tension in a string, meaning that, if a string attached to a body is suddenly stretched, the body will be accelerated, etc.

If we have any method by which we can subject a body to a force of a known magnitude, we can determine the mass of the body by measuring its acceleration under the action of the force, because by definition the mass equals the value of the force divided by that of the acceleration. Using everyday language, we may say that a body offers an opposition to having its state of motion changed; this opposition equals the product of the acceleration by the mass.

This concept of mass as a fundamental property of a body is due to Newton, although Galileo recognized its existence. Up to within very recent years it has been accepted as an elementary idea, i.e., it could not be shown that it was due to any other property of a

body. Now, however, we can prove, as will be done in a later lecture, that the fact of a body's having mass is in all probability to be attributed to more fundamental properties.

The second property of matter to which our attention is called by our muscle-sense is that to which we ordinarily give the name "weight." If one holds a body in his open hand, he is conscious of this; and if he allows it to fall, it will acquire an acceleration, which, as Galileo showed, is constant and the same for different bodies. If we call this acceleration g and the mass of the body m, we may describe the fact by saying that the "earth exerts a force mg upon the body." The idea occurred to Newton that there ought to be a similar action in the case of any two bodies, e.g., the earth and the moon or the sun; and he formulated a hypothesis as to the value of the force in the general case, which, so far as all known observations furnish us the truth, has been completely verified for bodies of moderate or large dimensions. The fundamental facts concerning this aspect of matter

are, then, (1) that any two bodies, if not too small, will, if free to move, approach each other, and (2) that the law of action is known. This property is called gravitational action, and will be described in another lecture; but it should be noted here that this gravitational force depends only upon the masses of bodies and their distances apart, not upon their material.

The third property of matter of which we spoke is the one to which our attention is called by our muscle-sense when we attempt to change the size or shape of a portion of matter. We recognize, as a matter of fact, a great number of properties all of which may, in a certain sense, be grouped together: rigidity, hardness, plasticity, etc. Certain of these are typical of what we call solids, others of liquids, others of gases. The fundamental fact is that the minute portions of all bodies act upon each other with forces which vary in all possible ways and which give to different bodies distinctive properties. These will be discussed later.

To summarize what has been said: every portion of matter has a definite property measured by its mass; two portions of matter, if not too small, attract each other according to a simple law which is independent of the kind of matter; two minute portions of matter act upon each other in a manner varying with the kind of matter. In addition to these properties which are concerned with either a single portion of matter or with two portions, there is another most important one which requires considerable discussion.

One of the most useful concepts in the history of science is that of the so-called "luminiferous ether," or as English writers call it "the æther." It is pictured as a universal medium, filling all known space; in this the minute portions of ordinary matter are supposed to exist, not unlike the motes of dust one sees in the air of a room when a ray of sunlight enters. It is assumed, further, to have mass and to be capable of sustaining a strain, like an elastic piece of matter. Perhaps I should use the expressions "was" and "has been,"

because, to many people, the idea of such a medium is not essential for a picture of nature; but it still plays, and undoubtedly will continue to do so, a useful part in our language and in our ideas. The primary function of the æther was that of serving as a vehicle of the cause of light. The sun produces in our eyes the sensation of light; and observations prove that whatever it is that the sun emits and that, when it reaches our eyes, produces light, it travels through space with a definite velocity of 30,000,000,000 (or 3×10^{10}) centimeters per second, or about 186,000 miles per second. We can picture this emission from the sun as consisting of discrete particles or as being a wave-motion. Particles in the ordinary sense it cannot be; and, if it is wave-motion, a medium is required, whose motion shall constitute the waves. The æther was the name given this medium. This conception of the æther may best be understood with reference to the concept of energy, to the discussion of which some time must be devoted.

We often introduce into science from every-

day language certain words to which we give exact definition. Thus the word "work" has been adopted and has been defined as having a value equal to the product of the values of a force and of the distance in its line of action through which its point of application moves. If I raise a heavy body vertically upward, I do work to an amount equal to the product of the weight by the height through which I raise the body. If I throw a ball whose mass is m so as to give it an acceleration a, a force ma is required, and, if I move my hand a distance x in producing the final velocity, I do the work max. These illustrate the two ways in which mechanical work may be done: (1) overcoming an opposing force, such as gravity; (2) producing acceleration. As the result of the work done upon a body in either of these ways, the body itself gains the power of doing work. Thus, the elevated body can do work by falling again; e.g., it may fall upon a board and bend it, or it may give motion to another body by striking it; the moving ball can do work; e.g., if it strikes another ball, it may

set it in motion. We must specially notice that in all cases, if the body does work, as stated, the power of doing more work is diminished. When a body has this power to do work, it is said to possess "energy." Therefore, as it does work, it loses energy; and the loss in energy in any case is defined to be equal to the work done. Conversely, when the body has work done upon it, it gains energy. If it gains this energy as the result of work done in overcoming a force, the energy is called "potential," e.g., an elevated body, a coiled watch-spring, a bent bow have potential energy. When the body has gained energy as the result of work done upon it in giving it motion, the energy is called "kinetic"; e.g., a falling body, a flying bullet, a revolving fly-wheel, all have kinetic energy. If a body whose mass is m is moving with a velocity v, the value of its kinetic energy may be shown to be $\frac{1}{2} mv^2$.

We may say, then, that a system has potential energy if it is not in its "natural" condition; thus a body may be thought to be in its natural condition with reference to the earth,

if it is in contact with it; and, when separated from the earth, the system, involving it and the earth, has potential energy. An elevated body falls if it is allowed to, a coiled spring uncoils if it is free to do so, a bent bow unbends when released, etc.; all of these "relaxing" processes involve a decrease in potential energy. Consequently, we may say that, when a system at rest has potential energy, all motions or changes which can take place of themselves occur in such a manner as to cause a decrease in potential energy. (This is a mode of describing actions which sometimes is preferable to the use of the word "force.")

If we picture to ourselves any series of mechanical processes involving work (e.g., let a compressed spiral spring give velocity to a ball, let this ball strike another ball giving it velocity, let this second ball strike a steel spring and bend it, etc.), we see that work is done at each of the stages, one body losing energy, the other body gaining it. In accordance with our definitions, the amount of energy which the one loses equals that gained by the other;

work is involved in the "transfer" of the energy. The total amount of energy, then, in the system remains unchanged. This constitutes the simplest illustration of the principle of the "conservation of energy."

I have purposely limited the discussion and the range of illustration to mechanical systems, i.e., to heavy bodies, springs, etc. There are, however, many cases involving work, which lie beyond such simple systems. Thus if I rub one rough body against another, if I stir a paddle in water, work is required; and yet there is no change in position and no apparent resulting motion to indicate a gain of energy by the rough bodies or by the water. We do find, however, that in both cases the bodies on which the work has been done indicate a rise in temperature and other so-called "heat-effects." This leads to the hypothesis that the work done in rubbing or in stirring has been spent in affecting the condition, not of the bodies as wholes, but of their minute portions; that is, if there are forces holding together these portions, work may have been

done in overcoming them; and, if these portions are free to move, kinetic energy may have been given them. This idea of considering the minute portions of a body as having both potential and kinetic energy, and of associating heat-effects and heat-phenomena in general with the changes in this internal energy of bodies, has been completely justified by experiments. By giving proper numbers to the various heat-quantities involved in these, we find that we can extend the principle of the conservation of energy so as to include the heat-phenomena as well as the ordinary motions of mechanics.

As has just been said, one of the results of doing work upon a body, so as to add energy to its minute parts, is rise in temperature. This same effect is produced if we expose a body to the sun's rays. This means that the body is gaining energy from the sun; the latter emits it and, after a lapse of time depending upon the distance of the sun from the earth, the body receives it. During the time of transit from the sun to the earth this

energy is referred to as "radiant energy" or "radiation." To all who believe in the reality of the æther this radiation is energy due to motions and strains in this medium; and it advances through the æther by the same general process as a wave travels along a stretched cord one of whose ends is vibrated. Part of this energy is kinetic; and part is to be considered potential.

One of the most interesting chapters of the history of science is that which contains the proof that every portion of matter in the universe is emitting radiant energy and also has the possibility of receiving such energy coming from other portions of matter. (It is evident that, if we can imagine this radiant energy as an entity by itself, there is no need of forming the conception of the æther to carry it; and this idea is now held by many.)

I cannot leave this subject of energy without referring briefly to one or two other manifestations of it. As we shall see when electrical phenomena are discussed in a later lecture, it requires work to produce electrification and

also to produce an electric current; this means that energy is associated with these two phenomena. In the case of ordinary charged bodies this energy is to be thought of as "potential," because motions take place in such a manner as to decrease it; further, as we so far understand the phenomenon of electrification, we are unable to show that it is associated with any motions. On the other hand, the phenomena of an electric current are essentially kinetic in character, motions are involved in every feature; and therefore the energy associated with a current is treated as "kinetic." It will be noted that neither in the case of electrification nor in that of the current have I spoken of the energy as being associated with anything. Those who believe in the æther think of it as being the seat of both these kinds of energy; while others consider the energy as having an independent existence.

We think then of energy as existing in many forms, associated with matter and with the æther, potential and kinetic; and to the

best of our knowledge the total amount of energy is conservative. Kinetic energy seems to us more easily understood, because when associated with ordinary matter its numerical value is $\frac{1}{2}mv^2$; potential energy, on the other hand, is a purely mathematical expression and cannot be analyzed into any mechanical picture; radiant energy, consisting as it does of wave-motion, is a concept which we can compare, for many purposes, with well-known mechanical disturbances.

Having thus far discussed the more obvious properties of material bodies, let us now consider what is known about their constitution. If we break into parts any piece of matter, e.g., a drop of water or a copper wire, each of the portions retains the properties of the whole. If the matter is homogeneous, we can imagine this process of subdivision continued almost indefinitely. All experiments go to prove that ultimately we shall obtain a portion of matter so minute that, although still being like the parent substance, it will, if broken up, give rise to portions of matter unlike this sub-

stance. This last minute fragment which still retains the properties of the original matter is called a "molecule." The fragments into which a molecule may be resolved are as a rule different; but, if they are all alike, the molecule is called "elementary," and the matter of which it formed a part is called an "element." The number of known elements is about 100, such as hydrogen, oxygen, mercury, lead, iron, etc. When in the course of ordinary chemical processes an elementary molecule is disrupted, the final fragments are called "atoms"; and the science of chemistry is based upon the completely verified hypotheses that the atoms of any element are all alike and that all molecules are composed of these atoms present in definite proportions. Thus, a molecule of water consists of two atoms of hydrogen and one of oxygen; a molecule of sulphuric acid consists of two atoms of hydrogen, one of sulphur, and four of oxygen.

We picture, therefore, every portion of matter as made up of molecules, which are in some cases bound together to form a solid,

in others not, as in a gas. But in all cases we know that the molecules are in unceasing motion. The evidence of this motion is most ample: evaporation of a liquid consists simply in the escape from the surface of its rapidly moving molecules; if any two portions of matter are brought into contact over a surface, a gradual intermingling of molecules through this surface may be observed, etc. In the case of a solid the molecules are held more or less rigidly in a fixed configuration, and simply oscillate to and fro; in a liquid the molecules wander with comparative freedom throughout the whole; in a gas there is still greater freedom of motion.

If we imagine a large space containing a great number of minute elastic spheres thrown in perfectly at random, they will collide, rebound, hit against the walls, etc. The velocity of any one sphere will change in direction and amount; but, if we can assume that there is a very large number of spheres present, we can calculate the pressure on the walls owing to the impact of the spheres, the proportion

of molecules which will probably have any specified velocity (under given conditions), etc. The properties of this set of spheres correspond in a wonderful manner with the observed properties of a gas. So perfect is the agreement that we feel justified in applying to actual gases certain formulæ deduced for the behavior of the set of spheres, and which thus enable us — assuming the justification of the method — to form a fairly clear idea as to the number of molecules present in any definite volume of the gas, the apparent volume of a molecule, the average speed of a molecule at any definite temperature, etc.[1]

The fact that the atoms constituting the molecules are also in vibratory motion cannot

[1] See Article "Molecules," *Encyc. Brit.*, eleventh edition. A few of these figures are as follows: —

Diameter of a hydrogen molecule is 2×10^{-8}cm.

Mean velocity at 0° C. of hydrogen molecules is 169,400 cm. per sec.

Number of molecules per cubic centimeter is 4×10^{19}. (This number is too large, as we shall see.)

The beautiful experiments of Perrin have shown us that these laws deduced from the kinetic theory of matter are verified in a wonderful manner by the motions of the minute groups of molecules, which are shown in what is called the "Brownian Movement."

be doubted. If two bodies, each consisting of simpler parts, undergo any kind of collision, the parts themselves must be affected. Further, the dimensions of the disturbances which accompany the radiant energy emitted by all bodies prove that the parts of the molecules are themselves in motion.

One of the most important of the conclusions to be drawn from the kinetic theory is a method leading to the determination, not of the mass of molecules, but of the ratio of the masses of the molecules of any two gases. In the hands of chemists this has led to the perfection of methods for measuring the ratio of the masses of the known atoms. Knowing these ratios, we may assign any number we wish to the atom of some one element, and then we have corresponding numbers for the atoms of all the other elements. These numbers are called "atomic weights"; and the system in most general use is based upon the selection of the number one for the hydrogen atom.

It has been proved, as the result of the work

of Newlands, Mendeléeff,[1] and others, that if the elements are grouped in a rectangular array, seven elements in a row, the arrangement being strictly in accordance with the atomic weights, the elements falling in any one column have many similar properties. This is known as the "periodic system." Of course, when the first grouping was made, it was necessary to use judgment in deciding where any element was to be placed, because it was always possible that there were still elements to be discovered; and therefore spaces had to be left for them. As time has gone on, and new elements have been found, they have fallen into place in the table, so that now nearly all the gaps have been filled. Of course, modifications have been made, such as the extension of each row so as to contain eight elements, and the collection of certain elements into distinct sub-groups, apart from the main table. Since the first discovery of this periodicity, many new features have been investigated proving that the elements in any one column must be considered

[1] See article "Element," *Encyc. Brit.*, eleventh edition.

as most intimately connected, in other words, their atoms must be believed to be related. For many years the evidence was entirely chemical; but within the past few years many additional facts have been discovered by means of physical investigations. Thus, the science of spectroscopy is based upon the fact that the molecules of each element, when in a gaseous condition, can be so excited as to emit radiant energy of a quality which is characteristic of that element; and when the spectra of the elements in any column of the table are compared, it is found that there are definite points of agreement. Similarly, when Roentgen rays traverse layers of different materials, it is found that varying proportions of the energy are absorbed by the matter, and that a secondary radiation is produced. This is found to be characteristic of the atoms making up the molecules of the matter; and, when the properties of the different elements are compared, it is found that they again arrange themselves in the periodic system. The obvious interpretation of the periodicity observed is that the atoms of

the elements in any one column are related in some such way as the following: one atom corresponds to a chain having ten links; the next atom, to a chain with eleven links, etc.; or starting with any atom, the one below it in the column is formed by the addition of a shell of matter, etc. The connection between the elements in any one row of the table is much less obvious, and is more numerical than chemical or physical.[1]

From the early days of chemistry fruitless attempts have been made, notably by Prout, to prove that all the elements are derived from combinations of different numbers of a single primordial atom. The first investigator to prove that a large number of different elements contained a common constituent was Sir J. J. Thomson, of the University of Cambridge. It has been known for many years that, when a gas is inclosed in a bulb and nearly exhausted,

[1] Rydberg has called attention to some most important connections between the atomic weights of the elements, all of which have a bearing on this question. *Zeit. für Anorg. Chem.*, vol. XIV, p. 66 (1897). See also Comstock, *Phil. Mag.*, vol. XV, p. 1 (1908).

so that the pressure is extremely small, the passage[1] of an electric current through the gas is accompanied by the production of a stream of rapidly moving particles called the "cathode rays." The current enters and leaves the bulb by metal connections; wires are inserted through the walls and end inside the bulb in metal plates. The one by which the current leaves is called the "cathode"; and the "cathode rays" have lines of motion perpendicular to its surface. In the investigation of the nature of these rays, Thomson proved that they were minute particles *identically alike, quite regardless of the nature of the gas originally put in the bulb;* and to them he gave the name "corpuscle." By means of a series of brilliant investigations he was able to measure the mass of a corpuscle, and he proved that it was approximately one eighteen hundredth of that of a hydrogen atom. I shall speak in a later lecture of what is meant by "electrical charges"; but you are all familiar doubtless

[1] See J. J. Thomson, *Conduction of Electricity through Gases* (1903).

with the fact that we distinguish between two conditions of electrification which we call positive and negative; and that we are able to measure charges. It has been known for many years that the particles composing the cathode rays in a vacuum tube were negatively charged, and Thomson devised a method which proved that the charges carried by all corpuscles were the same and which permitted the charge carried by any one particle to be measured. (It is the same as is carried by an atom of hydrogen in the process of electrolysis.) A corpuscle, then, is a negatively electrified particle of extraordinary small mass; and is, as Thomson showed, a common constituent of many elementary gases. Later experiments have shown that these same corpuscles are present in many other bodies. Whenever the temperature of any metal is raised sufficiently, there is a copious emission of corpuscles, and there is every reason for believing that there is this same emission at lower temperatures, but that our experimental methods are not as yet sufficiently delicate to detect them. Again, many bodies

emit corpuscles in large numbers when light falls upon them; and there is a group of bodies, known as radio-active substances, such as radium, uranium, thorium, etc., which emit corpuscles spontaneously. Still further evidence that corpuscles exist in all elements is furnished by what is called the "Zeeman effect." I have referred before to the characteristic radiation emitted from all elements when in a luminous gaseous condition. When such an emitting gas is placed in an intense magnetic field, e.g., between the poles of a strong magnet, there is a slight change in the character of the radiation. In order to account for this change it is necessary to assume the existence of small charged particles in connection with the atoms; and, when we compare the observed effect of the magnetic field with that calculated from theory, it is found that the existence of the corpuscle is demonstrated. Again, a dry gas in its natural condition is a very poor electrical conductor; but by certain processes it may be made an excellent one. When in this state, the gas is said to be "ionized"; and it

has been proved that this condition is due to the presence in the gas of corpuscles expelled from its molecules by the ionizing agent.

Taking into account, then, all evidence, we are safe in believing that corpuscles are an essential part of all atoms. What then forms the rest of the atoms? Here again some later experiments of Thomson offer knowledge. It was shown by Goldstein many years ago that, if the cathode in a "vacuum tube" is perforated, there is a special type of radiation which passes through these openings into the space back of the cathode when an electric current is passing through the gas. To this radiation he gave the name "canal rays."[1] When they were investigated carefully by Thomson, they were found to be positively charged particles, and although when using different gases in the bulb particles of different masses were observed, yet in all cases, no matter what the gas was, there were always present particles

[1] See J. J. Thomson, *loc. cit.;* also, *Phil. Mag.*, vol. xx, p. 752 (1910); vol. xxi, p. 225 (1911); vol. xxv, p. 209 (1912); *Proc. Roy. Inst.* (1911).

having the mass of a hydrogen atom; and in no case were there particles having a smaller mass. The electric charge carried by the hydrogen atom in these canal rays is identically the same as that characteristic of the corpuscle, only different in sign, being positive. The other particles present in these rays were found to be atoms of the molecules of the gases present in the bulb, or groups of these atoms.

As a matter of fact, when we examine all the ways in which electrical charges appear in nature, we find that there is every reason to believe that all charges are either equal to that of a corpuscle or are multiples of it, i.e., twice it, three times it, etc. In other words, we may call this charge a true atom of electricity, as was proposed, in another connection, by Helmholtz. Further, the atomic negative charge is always associated with the corpuscle; and the atomic plus charge has not yet been found associated with a particle less in mass than the hydrogen atom; but we must be careful to remember that we have not proved that all positively charged particles are com-

posed of parts identical with the hydrogen atom.

Another process by which we get evidence in regard to these elementary particles is that of radio-activity. The elements which possess this property such as uranium, radium, etc., besides emitting corpuscles as has been already stated, also expel positively charged particles. Rutherford and his associates have proved that these have the mass of a helium atom and carry twice the atomic charge.

We thus have conclusive evidence that all atoms of matter contain corpuscles and elementary positively charged particles; and, since all matter in its so-called "natural" condition is electrically neutral, each atom must in this condition contain equal quantities of positive and negative charges; so we can form a fairly clear idea of certain features of any atom.

We think of the positive charge as occupying the central part of the atom of any element, and inside it, or associated closely with it, we picture a corresponding number of the

minute corpuscles. To extend this idea so as to include atoms of different elements is not difficult.

A question which immediately suggests itself is this: Knowing that an atom contains these electrical charges, can it be shown that what we call mass, weight, elasticity and radiation are consequences of the existence of these charges? And, granting this, can we explain the periodicity of the elementary atoms, and the grouping of atoms to form molecules?

The fact that to a great extent we can do this is the most notable achievement of modern science; and the explanation of the various steps in the proof will form the subject of the succeeding lectures.

II

CORPUSCLES AND ATOMS; ELECTRICAL MASS

In the preceding lecture I described a few of the more important properties of matter; namely, mass, weight, elasticity, and radiation, and described certain experiments which proved that all atoms contained elementary electrical charges. Before we can show the connection between these ideas, it will be necessary to discuss the properties of an electric charge. We shall find that there are many properties which we can express in mathematical form, and that a knowledge of this enables us to predict with confidence what will happen under definite conditions. In this sense we can truly say that a great deal is known about electric charges; but when any student of physics is asked, as he is very often, "What is electricity?" he has great difficulty in giving an answer. This comes from the fact that the

one who asks the question is not satisfied by a statement of the mathematical laws which express our knowledge of electrical charges nor by the statement that we possess this knowledge; on the contrary, what the questioner really means is, "What does electricity look like? How does it feel?" etc. In other words the demand is made implicitly to describe electricity in terms of our senses. This is impossible. At the present state of our knowledge we must consider an electric charge as an elementary concept, and must attempt to explain our sense-reactions in terms of it, rather than to adopt the converse process.

The study of electric phenomena has been a favorite pursuit of philosophers from the dawn of science; and, owing to the efforts of brilliant experimenters and skillful mathematicians, we can now say that our knowledge of the subject is both extensive and accurate.[1] I must devote some time to a few of the elemen-

[1] See E. T. Whittaker, *A History of the Theories of Æther and Electricity from the Age of Descartes to the Close of the Nineteenth Century.* Dublin University Press Series (1910).

tary facts before speaking of their immediate bearing upon the subject in hand.

Whenever we separate two bodies which have been in close contact, we find that a new set of phenomena arise in connection with them, namely small bits of matter, such as pieces of paper, or particles of dust, placed near either of the two bodies are attracted towards it. Strictly speaking, the two bodies in contact must be of different materials; but as a matter of fact no two bodies — even if of the same material — are identically alike; there are slight differences in the arrangement of the molecules. We speak of these two bodies as being "charged," or "electrified." In the case of some bodies it is found that this power of attraction is localized in the surface which was in contact with the second body; whereas with other bodies the power to exhibit attraction is shown by its entire surface. The latter class of substances are called "conductors"; the former, "non-conductors." Thus, all metals are conductors; while glass, silk, flannel, rubber are non-conductors. If any charged

body is suspended by cords so as to be free to move, and if other charged bodies are brought near, it is observed that certain of these attract the suspended body, while all the others repel it. Thus we can divide all charged bodies into two groups: call those which attract by the name "A" and those which repel "B." By now suspending any one of the "A" group of charged bodies, we can prove that it is repelled by any other charge of the same group, but is attracted by any one of the "B" group. Similarly, if one of the "B" group is suspended, it is repelled by any charge of the same group, but attracted by any one of the other group. Thus we may say "like charges repel each other; unlike charges attract"; meaning by "like" charges those belonging to the same group. Various names have been given these two groups of charges; but those in universal use to-day are "positive" and "negative." The name "positive" is given to the charge observed on ordinary glass rods when they have been in contact with silk; and therefore all other charged bodies which

repel such a charged glass rod are also positively charged; while such charges as attract it are called "negative."

It is worth noting that it is a matter of complete indifference which type of charge is called positive and which negative. The names do not imply excess or deficit, but simply opposite actions or motions, because in many branches of mathematics a line drawn in one direction is called positive, and one drawn in the opposite, negative. Thus a line vertically upward might be called positive, in which case one drawn downward would be called negative. A mechanical analogy is as follows: if holding the ends of a rubber cord in our two hands we stretch it, the forces acting at the two ends are in opposite directions; if we called one positive, we would naturally call the other negative.

We must remember, further, that the question as to the character of charge which any body assumes, e.g., a glass rod, depends, not alone upon the body itself, but also upon the body which must be brought into contact with

it in order to produce the state of electrification. Thus a glass rod will be found to be negatively charged after it has been in contact with fur, such as a cat's skin. This shows that the state and quality of electrification depends upon the relative actions of the two kinds of molecules making up the bodies in contact.

We have described how we produce the condition known as electrification, and what is meant by positive and negative charges. Further experiments show that the production of a positive charge is always accompanied by that of a negative one; that is, for instance, when glass and silk are brought in contact and then separated, the glass is positively charged, the silk, negatively.

Through the brilliant experiments of Cavendish and of Faraday it was proved that it was proper to speak of the "quantity of a charge" and possible to give a number to it, in terms of any suitable unit. Since, when two bodies are in contact, there is no evidence of electrification, and when they are separated,

there is positive charge on one and negative on the other, the quantities of positive and negative charges must be equal; for then, when they were close together, there would have been no external action. Similarly, if at every point of a body there are equal amounts of positive and negative charges, there is no external evidence of a charge, and we would therefore call the body "neutral" with reference to electrification.

The discussion of the units in terms of which charges are expressed is too complicated to be given here. In practice there are two; one is called the "electrostatic unit"; the other, the "electromagnetic unit." One of the latter units equals 3×10^{10} of the former.

Since there is attraction between unlike charges, work is required on our part in order to separate the two bodies which have been in contact, and consequently there is energy associated with charges. This energy is spoken of as "electrostatic," for obvious reasons, and must be included under the general head of potential energy.

The exact mathematical expression of the phenomena observed in connection with charged bodies was given almost as soon as the phenomena themselves were discovered; and we now have at our disposal a most complete mathematical analysis.

Quite a different set of phenomena arise when the charges, instead of being at rest, are in motion. This state can be brought about in two ways: the charged body itself can be moved; or, the conductor being at rest, a difference in electrical conditions may be set up at two of its points. These conditions will be described more fully in a later lecture; but it is sufficient to say here that the result is to secure a motion of charges in the conductor. This constitutes an "electric current"; the "direction" of which is by definition that in which the positive charge is moving, or opposite to that in which the negative charge is moving. An electric current cannot, of course, be seen; but it is manifest to us by the fact that it is accompanied by what is called a "magnetic field"; i.e., a condition under

which a magnet — such as a compass needle — is acted upon by a force. Naturally work is required to produce this motion of the charges, and therefore a current is always associated with energy, which is called "electrokinetic." Here again the mathematical expression of the phenomena is most satisfactory.

I have spoken without any hesitation of positive and negative charges, and have shown how the names arose to describe certain conditions of experiment. I have also given in the last lecture the evidence in favor of believing in the existence of an entity which we have called the corpuscle and which is the atomic negative charge, and have said that an atom of matter in its "natural" condition does not show any evidence of a charge. In terms of positive and negative electricity, this is expressed by saying that in this condition an atom contains equal amounts of positive and negative charges. But we may look upon the question from a different standpoint. We may consider the atom of matter as an entity, and may say that its properties when it has lost a

corpuscle are those which we ordinarily attribute to a positive charge. In any case, whichever is our point of view, there are two distinct entities: either the two types of charges which combine to form an atom, or the atom and the corpuscle.

In this connection we should specially note that, although we have no proof of the existence of a positive charge carried on a body of less mass than a hydrogen atom, and although in this case the charge is the atomic one, this does not prove that the atomic positive charge has always the mass of a hydrogen atom. For, suppose that the neutral hydrogen atom contains three corpuscles and therefore three unit positive charges. When it loses one corpuscle, it will have left two corpuscles and three unit positive charges, and will consequently appear in all experiments to be charged with one positive unit, although in reality it contains three atomic positive charges. Therefore we cannot know the actual mass associated with a unit positive charge until we know definitely how many corpuscles there are in some one

neutral atom. Since this number is probably small, — not far from three for a hydrogen atom, as is now believed, — the mass associated with the unit positive charge must be large compared with that of the corpuscle, which is about one eighteen hundredth of the mass of a hydrogen atom. For this reason many people picture the volume occupied by the positive charge as being practically what we may call the volume of the atom.

One of the most important consequences of the mathematical development of the subject of electricity was the proof by Maxwell that any variation in the electrical conditions at any point is not accompanied instantly by corresponding changes in the electric force at all neighboring points, but, on the contrary, that it takes a finite time for the production of the changes, and that the more remote the point the greater is the time required. In other words, disturbances of electric forces are propagated with a finite velocity. Maxwell's theory went further, inasmuch as it gave the numerical value for this velocity. In the case of space

free of matter, e.g., between the sun and the earth, this velocity should be 30,000,000,000 (or 3×10^{10}) centimeters per second. This is the observed velocity of light; so we are justified in believing the phenomena of light, i.e., of radiant energy, to be due primarily to alterations of electric conditions, to electric oscillations, as they are called. In connection with the particular question which is in our minds, the explanation of the properties of matter, we see at once that the fact, previously emphasized, of all material bodies emitting radiant energy can be connected with the presence in the material atoms of the electrical charges, provided these charges are in such a state of motion as to give rise to electric disturbances. What this state is will appear presently.

I must now call your attention to what, for our present purposes, is the most important property of a charge. When a charge is at rest it has associated with it, as has been said, a quantity of potential energy; and, when in motion of translation, it has in addition a

definite amount of kinetic energy, corresponding to the work required to set it in motion. A moving charge is equivalent to a current; and this kinetic energy is manifest to us by the magnetic forces which are characteristic of a current. This means that, if a charged body is given a velocity of translation, work has to be done both in giving acceleration to the material body and in giving it to the charge; or, expressed differently, a charge of itself has mass, inasmuch as work is required to change its motion. The question immediately arises, since we have proved that all material atoms contain charges, may not the mass observed in the case of any material body be due, in reality, to the charges contained by its atoms? If this were true, we would have an explanation of mass. One method of testing this idea is to calculate the energy which a charge has owing to its motion, and thus deduce its effective mass; then, knowing the charges associated with atoms, we may be able to decide the question.

The first to make a calculation with this

purpose, and the first to propose this electrical explanation of mass was J. J. Thomson.[1] He considered the motion of a charged particle, and assumed that its electrical action was limited to the region outside a minute sphere of radius a, described around the particle as a center. Then, if the charge has a value e, and if its velocity of translation is v, the kinetic energy due to its motion is found by calculation to be $\frac{1}{2}\frac{2}{3}\frac{e^2}{a}v^2$, provided the velocity is not too great. Now, the energy of translation of a material body of mass m is, as we have seen, $\frac{1}{2}mv^2$. It is evident, therefore, that the "mass" of the charge is $\frac{2}{3}\frac{e^2}{a}$. It is impossible to compare this value of the "electrical mass" with that observed for any charged body owing to the difficulty of knowing the value of the distance a at which we consider the action

[1] See *Phil. Mag.*, vol. XI, p. 227 (1881). J. J. Thomson, *Electricity and Matter* (New York, 1904); *The Corpuscular Theory of Matter* (London, 1907); article "Matter," *Encyc. Brit.*, eleventh edition. H. A. Lorentz, *The Theory of Electrons* (Leipzig, 1909).

to begin. Fortunately, however, there is a method by which the idea may be tested.

When the calculation of the mass of a moving charge is made for the case of great velocity, it is found that the mass increases as the velocity increases; and, assuming that the mass of a charged particle is due entirely to its charge, Thomson calculated the law connecting mass and velocity. An opportunity soon arose for testing this. As you all know, radioactive substances, such as radium, emit several types of radiation; one of these, called the beta rays, consists of negatively charged particles, which are expelled with velocities approaching that of light. These rays have different velocities; and, by using a method devised by Thomson, Kaufmann, and later Bucherer,[1] measured the velocities and masses of these particles, assuming, as they were justified in doing, that the electric charge was the atomic one. They found that the particles having the greater velocity had the greater

[1] *Ann. der Physik*, vol. XXVIII, p. 513 (1909); vol. XXX, p. 974 (1909). See also article by Wolz, *ibid.*, vol. XXX, p. 273 (1909).

mass, and the connection between mass and velocity was exactly what one would expect, assuming that the mass of the particle was entirely due to its charge. This was a most striking result. Since the beta particles are identical with the corpuscles which are common constituents of all atoms, and since their mass is entirely electrical in origin, we can state definitely that part at least of the mass of any body is due to its corpuscles. Whether or not the entire mass is of this electric origin will depend upon the number of corpuscles present in the atoms. Before, however, taking up this point, I wish to present to you a different way of considering this question of the mass of an electric charge.

Up to this point we have discussed simply the total amount of the mass of the charge as indicated by its kinetic energy in the surrounding medium when it is in motion. If we think of mass as being given by momentum, Thomson has shown that in reality this mass is best thought of, not as a property of the particle itself, but rather as one of the region

surrounding the particle. This region contains potential energy, as has been said repeatedly; and, as the charged particle moves, it carries with it this energy. Thomson proved that the simplest way of describing the mass of a charged particle was to assign a definite amount of mass to each element of space which contains potential energy, the one being proportional to the other. The exact statement is that the potential energy in any minute volume equals $\frac{1}{2}$ (electrical mass in that volume) $\times$ (velocity of light)^2.

One must note carefully that the momenta of these minute elements of mass distributed around the moving charged particle are not in general in the same direction as that of the motion of the particle; and therefore the mass of the charge, as shown by its momentum, is not equal to the sum of the elementary masses. Another fact which must be emphasized is that, inasmuch as a corpuscle cannot exist by itself, but is always associated with a positive charge, even though far separated from it, this electrostatic energy is not to be attributed

to the corpuscle alone, but to the two equal and opposite charges. However, if the corpuscle is much smaller in volume than the positive charge, the larger part of the energy is concentrated around it.

This association of mass and potential energy is perfectly general and holds for all velocities of the particle, and for every case where there is electrostatic energy. An illustration of this fact is afforded by the effects of radiant energy, the energy which is emitted by all material bodies and which is traversing space with the enormous velocity of 3×10^{10} centimeters per second. This is in part kinetic and in part potential. It has been known for many years that it was a consequence of the mathematical equations which state our knowledge of electrical phenomena and also a consequence of our theories concerning heat-phenomena that radiant energy falling upon any body should give it a push and that the body emitting radiant energy should experience a recoil. These predictions of theory have been verified by direct experiment. This push and recoil are

of course illustrations of momentum. When we calculate the mass as shown by this light pressure and compare it with the amount of potential energy in the radiation, it is found that there is the same proportionality as in the case of the potential energy of a charged particle. Further, Hasenöhrl[1] has shown that, if we had a closed box inside which radiation is moving to and fro, the force required to produce a definite acceleration of the box is greater than it would be if there were no radiation, thus showing that the radiation possesses mass. One must add that the fact of there always being a definite mass associated with a definite amount of potential energy, regardless of whether the energy is that of a static charge or is part of radiation traversing space at an enormous velocity, is most remarkable.

[1] *Sitz. Ber. Wiener Akad.*, 2a. vol. CXVI, p. 1391 (1907); vol. CXVII, p. 207 (1908). Comstock has shown (*Phil. Mag.*, vol. XV, p. 1) that "if second order terms in the velocity be neglected the mass [of a purely electrical system] is a simple constant $\left[\frac{4}{3}\frac{1}{v^2}\right]$ multiplied by the total included electromagnetic energy," where v is the velocity of light.

In all his earlier papers on the subject of the mass associated with electric charges, Thomson described the phenomena as due to the mass of certain portions of the æther, which he called "bound æther." For many purposes it is convenient to describe the properties of charged bodies in terms of what Faraday called "lines of force." If we consider a corpuscle at rest, the line of action of the force between it and any small positively charged body in the neighborhood is the straight line joining them; and we can associate these radial lines, drawn from the center of the corpuscle, with the corpuscle itself, calling them "lines of force." Most writers have pictured the space around any charged conductor as *filled* with these lines, and for convenience have divided the space into certain volumes bounded by the lines, thus forming what may be called "tubes of force." Thomson, on the other hand, considers the tubes starting from the charged conductor as of uniform cross-section throughout their entire length, so that only a small portion of the space is

occupied by the tubes. He imagines a definite amount of æther "bound" to these tubes, so that, if they move lengthwise, i.e., in the direction of the tube itself, there is no motion of the æther; but, if they move transversely, this bound æther is carried along in the motion. By attributing mass to the æther it is at once evident, then, how we can say that an electric charge possesses mass. If, on the other hand, we do not postulate the existence of the æther, but consider energy as an entity, we keep all of our geometry and so do not alter our mental picture, but simply change our mode of description. There are certain advantages in Thomson's earlier point of view, because there is a most interesting analogy which one can draw between the motion through the æther of a charged body with its rod-like tubes of force and that through a fluid of a solid having long elastic pins stuck in it. Whenever a solid mass moves through a fluid, portions of the latter are set in motion also; and so the apparent mass of the solid is increased, e.g., the impulse required to bring to rest the solid

when moving through the fluid is greater than it would be if the fluid were absent. Further, when an oblong-shaped solid is moving through a fluid, it will turn, unless prevented, so as to present its longer side perpendicular to the line of motion. Thus, a falling leaf never drops with its edge down, but always flutters towards the earth with its broad face parallel to the earth. So in the case of a solid and its pins, the latter will all tend to place themselves at right angles to the line of motion. As a matter of fact the same statement is true of the lines of force associated with a moving charged body, as was first shown by Heaviside; the lines tend to collect into an equatorial plane perpendicular to the line of motion; and the increase in mass of a charge when its velocity becomes very great may be shown to be connected with this change in the geometry of the "tubes of force." Thomson has used this analogy most skillfully in his discussion of the properties of moving charges; but its usefulness vanishes if we discard the conception of the æther.

In considering the mass of an electric charge as distributed throughout the regions of space where there is electrostatic energy owing to the charge, we see that strictly speaking a single corpuscle (with its complementary positive charge) produces mass throughout all space, out to infinity, because its influence extends that far, and every portion of space contains a certain amount of energy due to it. If there are two corpuscles, any element of volume in the surrounding space will contain energy due to each of them; and so the masses due to two corpuscles will occupy the same space! The relative amounts of the mass, though, in regions close to and far from a corpuscle may be calculated from Thomson's formula; and it is found that practically all of the mass is concentrated in a region extremely near the corpuscle, less than one millionth of its mass being outside what we may call "atomic distance," so we may still picture the corpuscles as true particles, each practically distinct from its neighbors.

A much more serious question arises, how-

ever, when we ask whether we can account for the entire mass of an atom as due to the electric charges associated with it. I have shown in the first lecture that corpuscles exist in connection with the atoms of all kinds of matter, and that with every corpuscle there must be associated an equivalent positive charge. In the calculation of the mass of a charge, Thomson assumed that the charge existed by itself, that is, that the equivalent charge of opposite sign was so far removed as to allow its influence to be neglected. If this complementary charge is in close proximity, however, to the charged body, the potential energy is decreased, and therefore so is the electric mass. Our experiments measure the mass and charge of a corpuscle when it is expelled from its atom; but, when it forms part of the atom, and is therefore associated with a positive charge, the mass due to the potential energy is less than that found for the corpuscle when free from the atom. The mass in the latter case is about one eighteen hundredth of that of a hydrogen atom; let us assume, for the sake

of having a definite quantity, that when in a hydrogen atom the corpuscle has a mass one two thousandth that of the atom. (The actual value will depend upon the number of corpuscles, their distribution, etc.) Then, in order to account for the total mass of a hydrogen atom as due to the potential energy of the charges, we must assume the existence in the hydrogen atom of two thousand corpuscles. But, as opposed to this, stands the fact that a great many lines of investigation indicate clearly that a hydrogen atom has a very small number of corpuscles, possibly not more than three, and that the number of corpuscles in any atom is proportional to its atomic weight, e.g., an oxygen atom has sixteen times as many as has a hydrogen atom, etc.[1] If this is true, the mass due to the potential energy of the corpuscles and the complementary positive charge amounts to only a small part of the total mass of the atom. It is possible, of course, that the

[1] J. J. Thomson, *The Corpuscular Theory of Matter* (London, 1907); *Phil. Mag.* (VI), vol. XXIII, p. 451 (1912). H. A. Wilson, *Proc. Amer. Phil. Soc.*, vol. I, p. 371 (1911). J. A. Crowther, *Proc. Roy. Soc.*, vol. LXXXIV, p. 226 (1911).

experiments bearing upon the number of corpuscles in an atom are not conclusive; it may be that they give us knowledge only of certain groups of corpuscles, not of others. If, however, we accept the idea of a small number of corpuscles in an atom, we are forced to the adoption of one of two hypotheses:—

(1) Part of the mass of an atom is due to mechanical as distinct from electrical causes.

(2) Mass is due to other "electrical" causes than electrostatic energy alone.

In this connection we must note the difference in "size" which Thomson attributes to the positive and negative charges in an atom. Grant that a hydrogen atom has three corpuscles; then the entire volume of the atom is considered as divided practically into three equal parts, each of which is to be thought of as the volume of a unit positive charge. Consequently, the ultimate electric doublet, consisting of a corpuscle and its complementary positive charge, form a group of a minute particle joined by lines of force to a rela-

tively large volume. Thomson in speaking of this has again resorted to the analogy of a solid moving through a fluid. If we imagine a solid shaped like a dumb-bell, but having one of the balls much larger than the other, it is evident that in moving through a fluid by far the larger proportion of the fluid which is set in motion by the solid is due to the larger ball. By way of analogy we may compare the large ball to the positive charge, the small ball to the negative one, and the connecting bar to the tube of force. The negative charge as such would then not drag with it any æther practically, the tube of force would carry a little, that due to the potential energy; but the largest amount would be associated with the positive charge. Direct experimental evidence bearing upon this does not exist. However, there is nothing in the nature of the idea of electrical mass or in the concept of a corpuscle which requires us to picture the positive change as having a volume practically equivalent to that of the atom; it may be concentrated into a comparatively small nucleus

at the center of the atom — as has been in fact proposed by Rutherford.

I have carried you in a rather hurried manner through the evidence that all atoms, no matter with what element they are associated, contain corpuscles, i.e., atomic negative charges, and also complementary positive charges, and have stated that experiments point to the idea that the number of corpuscles in an atom is proportional to its atomic weight. Expressed differently, this means that the mass of any atom is proportional to the number of corpuscles it contains.

In the remaining part of this lecture I wish to describe in some detail the experiments upon which our knowledge rests.

One of the most important facts upon which the theory is based is that there is an atomic electric charge, which is always associated with a corpuscle. This means that there is a definite charge so small that none smaller has been observed, and such that all charges measured are either equal to this or multiples of it. This concept of an atomic charge is due

to Faraday and was used by him to describe the phenomena of conduction of an electric current by a solution of salt or acid in water. The idea of its extension to all charges is due to J. J. Thomson; and he was the first to prove that there was an atomic charge on a corpuscle, equal to that observed in Faraday's experiments. His work on this point, although the earliest, is not the best, as later experimenters have improved his methods. The most interesting investigation on the subject, in view of the theoretical simplicity of the observations and the clearness of the conclusions, is the one carried through in such a masterly manner by Professor Millikan, of the University of Chicago.[1] In devising his method he took advantage of the following well-known facts: —

(1) A minute drop of oil or mercury or any liquid will fall under the influence of gravity at a rate depending upon its properties and those of the surrounding gas. (The laws for

[1] *Popular Science Monthly*, April, 1912; *Physical Review*, vol. XXXII, p. 349 (1911); February, 1913.

this fall have been investigated by Stokes, by Cunningham, and by Millikan himself.)

(2) It is possible by various means to add a charge to these drops; and therefore, by applying an electric force in a vertical direction, one can neutralize this falling of a drop or reverse its motion.

In the actual experiments a single charged drop was isolated and carefully watched; it fell through a known distance, the time being noted; an electric field of known intensity was applied so as to reverse its motion and the time of rise was observed; it was again allowed to fall, etc. The formulæ which apply to these conditions lead at once to a value for the charge carried by the drop; and Millikan's observations prove beyond any shadow of doubt that this charge is of an atomic nature. The value obtained for the atomic charge was 4.774×10^{-10} electrostatic units, or 1.591×10^{-20} when expressed in the "electromagnetic system." In these experiments some drops were charged positively, some negatively; some had a unit charge; others, multiples of this.

The correctness of his method has been questioned; but he has shown to the satisfaction of all that the criticisms are not well founded. When considered in all its aspects this investigation by Professor Millikan may be considered one of the most brilliant ever carried on in this country.

The value of the atomic charge carried in experiments like those of Faraday cannot be determined directly; but the ratio of this to the mass of the particle carrying the charge may be. This is 9648.9, when the carrier of the charge is a hydrogen atom, using the electromagnetic system of units. The fact that Faraday's atomic charge is identical with the corpuscular charge was proved by Townsend and also by H. A. Wilson; and therefore knowing this charge to be 1.59×10^{-20}, it follows that the mass of a hydrogen atom is *1.65×10^{-24} grams*. From a knowledge of this mass and the atomic weights, we can calculate at once the mass of the atom of any element.

It is well known from experiments on the

liberation of hydrogen gas by passing an electric current through solutions of acid in water that one electromagnetic unit of charge liberates 1.1657 cubic centimeters of the gas. Each molecule of the gas has been formed out of two atoms, each of which carries the atomic charge; therefore, if there are N molecules in each cubic centimeter of the gas, the total charge carried must be $2N \times 1.1657 \times 1.59 \times 10^{-20}$. But this must equal 1. Hence we can calculate, $N = 2.7 \times 10^{19}$. (This is the number of molecules per cubic centimeter of any gas at 0° C and at normal barometric pressure.) To give an idea of the enormous magnitude of this number, Thomson calls attention to the fact that, if a person were to count and collect molecules at the rate of one per second for one hundred million years, he would not have sufficient for chemical detection.

In order to determine the mass of the corpuscle, Thomson made use of a most ingenious method. If a charged body is moving rapidly, it has, as has been stated before, both an electric and a magnetic field; so it will be

acted on itself by both electric and magnetic forces. Under the action of either one the path of the moving charge would be deflected; and therefore, by choosing suitable forces of the two types, we may make one neutralize the effect of the other, as will be shown by the path of the particle remaining unchanged. When the proper formulæ are applied to this condition, it is found that we can determine the velocity of the moving charge and the ratio of its charge to its mass, if we measure the two balancing forces. When this method is used with the particles constituting the cathode rays, and with those emitted by hot bodies or by bodies under the action of light, it is found that, although the velocities may vary greatly, the ratio of charge to mass is the same for them all,[1] its value being 1.77×10^7. Knowing the value of the charge, the value of the mass is thus seen to be 9.00×10^{-28}, which is about one eighteen hundredth of that of the hydrogen atom. It was

[1] See article by Wolz, *Ann. der Physik*, vol. xxx, p. 273 (1909). The value adopted by him is 1.7674×10^7.

by simple modifications of Thomson's method that the properties of the beta rays emitted by radium and other radio-active bodies were studied, and that it was proved that, as the velocity of the particles becomes very great, the mass increases. (This interpretation is, of course, based upon the assumption that the value of the electric charge remains unchanged; but there is no reason for doubting this.)

When it comes to the question of the charge and mass of the elementary positive particles, there are two investigations which must be mentioned. The first of these is that by Thomson upon the nature of the canal rays in vacuum tubes, to which brief reference has been made before. He determined by the method just described the velocity and the ratio of charge to mass of the particles constituting these rays, and found, in the case of any definite gas, that there were carriers of different masses; one corresponded always to a hydrogen atom no matter what the gas was. The other investigation was a most wonderful

series of experiments concerning the properties of radium, made by Rutherford and his associates. As has been said before, radium emits corpuscles and also positively charged particles of much larger mass, which are called alpha particles. Geiger and Rutherford devised two methods by which the actual number of alpha particles emitted per second by a given mass of radium may be counted, and proved that these were charged helium atoms. Then, knowing from the application of Thomson's method, the ratio of the charge to the mass of each particle, it was shown that each particle carried a double atomic charge.[1]

I cannot pass by these brilliant experiments without calling your special attention to at least one other feature. Since the foundation of modern science people have believed in the existence of molecules and atoms, but who has had hope of ever securing any knowl-

[1] Rutherford and Geiger, *Proc. Roy. Soc.*, vol. LXXXI, pp. 141 and 162 (1908). Regener, *Sitz. Ber. Berlin Akad.*, vol. XXXVIII, p. 948 (1909). Geiger and Rutherford have also counted the alpha particles emitted by uranium and thorium: *Phil. Mag.*, vol. XX, p. 691 (1910). See also *Phil. Mag.*, vol. XXIV, p. 618 (1912).

edge of an individual atom? Its size is so extraordinarily minute and its mass so far beyond the power of any balance to recognize, even granting the possibility of isolating it. But, here, in the experiments of Rutherford we can actually count the atoms of helium as they are ejected from the parent radium. The property of the atom which is made use of is not its size nor its mass, but its velocity of motion. When a charged particle moves with sufficient speed through a gas, the latter is ionized, becoming a good electric conductor; and this fact may be easily recognized by the use of well-known electrical instruments. (The method is not unlike one that might be used in counting the number of bullets fired from a gun by observing the holes made in a target.) Again, when an alpha particle strikes certain phosphorescent substances, such as Sidot's blende, there is a brilliant instantaneous emission of light, which is called a "scintillation." Taking advantage of these facts, Rutherford was able actually to count the individual atoms. His experiments showed that

one gram of radium emits 3.4×10^{10} alpha particles each second, and that each particle carries 3.1×10^{-20} electromagnetic charge. Since each particle carries a double atomic charge, this gives for that quantity the value 1.55×10^{-20} which is in close agreement with the value given by Millikan, viz., 1.59×10^{-20}.

In deducing the value of the mass of a corpuscle it is evident that some assumption must be made in regard to the space occupied by it. Some authors have considered the charge distributed over the surface of a conducting sphere; others, as distributed uniformly through the volume of a non-conducting sphere. It is difficult to say what meaning, if any, these words — conducting and non-conducting — would have in speaking of a corpuscle; and, as a matter of fact, the formulæ deduced are all the same provided the velocity of motion of the charged body is not too great. In deducing his original formula for the mass of a charge, Thomson assumed that the action was the same as if the charge were concentrated at a point and that the force began at

an arbitrary distance from this point. Under these conditions, if we call a this distance, it is not difficult to prove that the formula connecting mass and charge is

$$m = \frac{2}{3}\frac{e^2}{a}$$

Having by experiments on the corpuscle determined its mass and charge, we may substitute these values in this formula, and thus obtain the value of a, i.e., the radius of the "sphere of action" of the corpuscle. This is found to be 2×10^{-13} *cm.*

When we discuss rigidly the mass of a charged body having a great velocity, we cannot shirk the question as to the distribution of the charge; because we find that the value deduced for the mass depends upon our assumptions. Lorentz, who has been most successful in solving this problem, has deduced a formula, which, so far as experimental evidence at present goes, has been verified. He assumes that the charge of the corpuscle may be considered distributed over a conducting surface which at small velocities is a sphere,

but at great velocities becomes flattened into an ellipsoid having its broader face at right angles to the motion.[1]

[1] H. A. Lorentz, *The Theory of Electrons* (Leipzig, 1909).

III

RADIO-ACTIVITY; GRAVITATION

Every one in the audience remembers, doubtless, the great interest, almost excitement, aroused by the discovery of the Roentgen rays in 1895. There certainly was a great deal that was spectacular in their properties; but from the standpoint of addition to knowledge, the most important consequence of their discovery was an indirect one. You may remember that the seat of production of the Roentgen rays is the solid obstacle which stops the cathode rays in a vacuum tube; and that in the original experiments of Roentgen, this obstacle was a portion of the glass wall of the tube. A conspicuous fact in any vacuum tube is the brilliant luminescence of the glass wall where struck by the cathode rays; so in these experiments we have the glass wall exhibiting two phenomena: it is emitting light under the stimulation of the impacts of the cathode par-

ticles and it is the source of the Roentgen rays. The idea occurred to the French physicist, Henri Becquerel, to investigate the possibility of there being a similar emission of Roentgen rays when a body is emitting light under what we may call artificial stimulation. The salts of uranium have been known for some time to have the property of continuing to emit light after having been exposed to light. (Bodies having this property are said to be "phosphorescent.") Becquerel, then, having exposed some uranium salts to light, carried on a series of researches to see if they emitted any other radiation than light. He found that they did; but that the new radiation was different in essential respects from Roentgen rays. This was the primary discovery in the field of what is now called radio-activity.[1] Owing to the investigations of Becquerel, of the two Curies, — husband and wife, — of Rutherford, of Boltwood in this country, and

[1] Rutherford, *Radio-Activity* (1905); *Radio-Active Transformations* (1906); *Radio-Active Substances and their Radiations* (1913). Madame Curie, *Traité de Radio activité*, 2 vols. (1910). *Jahrbuch der Radioaktivität und Elektionik.*

many others inspired by them, the science of radio-activity now rests upon a foundation of well-established facts and inspiring theory.

Several other substances have been found occurring in natural ores which have the property of radio-activity; the two best known are radium and thorium. All of these are characterized by the spontaneous emission of several types of radiation, which have received the names alpha, beta, and gamma rays. The alpha rays are atoms of helium, each carrying a positive double atomic charge; the beta rays are corpuscles; the gamma rays are in all probability identical with a certain type of Roentgen rays, being a form of radiant energy. Rutherford advanced the accepted theory of these phenomena, and has by his own investigations contributed largely to its proof. The fundamental idea is that, being given a radioactive substance, a certain number of its atoms are undergoing a transformation into a different type of atom, the transformation consisting in the emission of the rays and in the

rearrangement of the remaining parts of the atom. Thus, we picture such an atom as being made up of parts and as becoming unstable owing to certain causes; it then "breaks down" and some of the constituent parts are ejected; the remaining parts rearrange themselves, forming a new atom; if this new atom then becomes unstable, it may break down, ejecting particles, and permitting another atom to form; etc. It is important to note that this instability of the atom does not depend upon its age or upon any known physical condition; and therefore it is hardly correct to speak of the atom *becoming unstable*. By his investigations Rutherford has proved that this hypothesis of radio-active transformation accounts for the observed facts. In certain steps an alpha particle is emitted; in others a beta particle; and in a few there is no emission but simply an internal rearrangement of the parts. It has been shown very recently that a certain proportion of atoms of a definite kind may lose an alpha particle, while the rest of these atoms lose a beta particle; thus one type

of atom gives rise directly to two different kinds.[1]

By the very recent work[2] of Dr. Gray and Sir William Ramsay certain features of this theory have been proved conclusively by quantitative measurements. They perfected a balance capable of detecting a change of the weights in the balance-pans of one hundred thousandth of a milligram, a marvelous exhibition of experimental skill. By means of this they succeeded in measuring the atomic weight of radium emanation, which according to the theory is formed from radium by the emission of an alpha particle. The atomic weight of radium is known to be 226.4, that of an alpha particle is 4; and therefore by Rutherford's theory the atomic weight of the radium emanation should be $226.4-4$, or 222.4. These investigators determined it to be 223, which is a wonderful agreement when one considers the difficulties of the research.

[1] *Physik. Zeitsch.*, p. 369 (1911); pp. 623, 699 (1912). *Proc. Phys. Soc. of London*, vol. XXIV, p. 50 (1911).

[2] *Proc. Roy. Soc.*, vol. LXXXIV, p. 536 (1911).

The facts so far as they are known to-day, are that a

Uranium atom loses an alpha particle, becoming a
$Uranium_2$ atom ;[1] this loses an alpha particle, becoming a
Uranium X atom ; this loses a beta particle, becoming an
Ionium atom ; this loses an alpha particle, becoming a
Radium atom ; this loses an alpha and a beta[2] particle becoming a
Radium emanation atom ; this loses an alpha particle, becoming a
Radium A atom ; this loses an alpha particle becoming a
Radium B atom ; this loses a beta particle, becoming a
Radium C atom ; this loses an alpha and a beta particle, becoming a
Radium D atom ; this loses a beta[2] particle, becoming a
Radium E atom ; this loses a beta particle, becoming a
Radium F (Polonium) atom ; this loses an alpha particle, becoming a Lead atom.
A very small proportion of Radium C atoms form what are called Radium C_2 atoms ; these lose beta particles, etc.

By some process, at present unknown, a Uranium atom gives rise to an Actinium atom ; it transforms into a
Radio-actinium atom ; this loses an alpha and a beta particle, becoming an

[1] Madame Curie calls the intermediate product between Uranium and Uranium X Radiouranium. A small portion of the $Uranium_2$ atoms form by disintegration a different atom from Uranium X ; this has been called Uranium Y.

[2] These beta particles are corpuscles having a comparatively slow velocity.

Actinium X atom; this loses an alpha particle, becoming an
Actinium emanation atom; this loses an alpha particle, becoming an
Actinium A atom; this loses an alpha particle, becoming an
Actinium B atom; this loses a beta particle, becoming an
Actinium C atom; this loses an alpha particle, becoming an
Actinium D atom; this loses a beta particle.

A Thorium atom loses an alpha particle and becomes a
Mesothorium I atom; this transforms into a
Mesothorium II atom; this loses a beta particle, becoming a
Radiothorium atom; this loses an alpha particle, becoming a
Thorium X atom; this loses an alpha and a beta particle, becoming a
Thorium emanation atom; this loses an alpha particle, becoming a
Thorium A atom; this loses an alpha particle, becoming a
Thorium B atom; this loses a beta particle, becoming a
Thorium C atom; this loses an alpha particle, becoming a
Thorium D atom; this loses a beta particle.
Some of the Thorium C atoms lose beta particles, becoming what are called Thorium C_2 atoms; these lose alpha particles, etc.

It is thus seen that several well-known elements owe their origin to the disintegration of the atoms of other elements, and there are

now known over thirty radio-active atoms. Some appear as solids, others as gases. Further it should be noted that, if we allow these radio-active transformations to go on inside a closed space, there is a gradual accumulation of helium gas. This is due to the fact that the alpha particles are helium atoms; and these become the ordinary gaseous molecules as soon as they become electrically neutral by attaching corpuscles to themselves. Rutherford proved this conclusively by allowing alpha particles to penetrate by impact into a tube having very thin walls, and then showing that helium gas collects in the tube.[1] This gas is a so-called non-atomic one; i.e., each of its molecules consists of simply one atom. It is most easily detected by the character of light-radiation it emits when an electric discharge is passed through it.

The time required for a definite proportion of a given quantity of any one of the radio-active atoms to break down into the next atom

[1] Rutherford and Royds, *Chem. News*, vol. XCIX, p. 49 (1909); *Phil. Mag.*, vol. XVII, p. 281 (1909). See also Boltwood and Rutherford, *Phil. Mag.*, vol. XXII, p. 586 (1911).

in the series is perfectly characteristic of the change, and has been measured with a marked degree of accuracy. This time-element is generally given as the number of seconds, minutes, or years required for one half of the atoms to be transformed. It varies from one five hundredth of a second in the case of Actinium A to five billion years for Uranium. The law obeyed is that characteristic of a theory of probability, and offers no suggestion as to an explanation.

With reference to the special subject of this course two facts stand out with clearness: one is that here we have plain evidence of a simple connection between atoms of different elements; the other is that the potential energy of a radio-active atom is being decreased by the emission of the various types of radiation. (For the sake of analogy we can think of a coiled spring and bullet such as constitute a toy gun; the compressed spring has potential energy, the bullet when expelled gains kinetic energy at the expense of the loss of potential energy by the spring.)

Therefore in proposing any general scheme for the constitution of an atom, these facts in regard to radio-active transformations are of the utmost importance; and, inasmuch as we have here definite and known losses of potential energy, we can test certain of our ideas concerning weight and mass, so far as the latter is due to electrical causes.

Weight is the second fundamental property of matter, which I mentioned in the first lecture. We speak of a body as "heavy" or "light," meaning to convey the idea of the intensity of stimulation of our muscle-senses when we keep the body from falling towards the earth by suspending it in our hand or on our back. This means that there is a force acting between the suspended body and the earth; and to this force we give the name "weight." Newton made the hypothesis that there was a similar force between any two material bodies, and proposed a law for its action, which is known as Newton's "Law of Gravitation." It may be expressed as follows: let us consider two particles of matter whose masses are known quan-

tities, m_1 and m_2, and whose distance apart is r, then there is a force between them proportional to the product of the values of the masses and inversely to the square of the value of the distance. The real importance of this statement or hypothesis lies as much in what is omitted purposely as in what is said explicitly; for, in order to make the law complete, we must add: this force of attraction is independent of the nature or condition of the bodies, i.e., whether they are solid or not, whether they are hot or cold, whether they are made of one element or another or any combination of elements; it is independent of the medium surrounding the bodies or separating them. In other words, the only elementary ideas involved in gravitation are the masses of the parts concerned and their distance apart, a most remarkable fact, if true.

In order to see if this hypothesis of his did truly describe the phenomena of nature, Newton proceeded to make some experiments of his own, and also drew various deductions from it so as to compare them with known facts

of astronomy. His first difficulty was a mathematical one. The hypothesis as made applies to two *particles*, i.e., to portions of matter occupying such minute volumes that we can neglect their dimensions in comparison with their distance from each other; but if it is to be applied to observations on large bodies, such as any we actually work with or any of the astronomical bodies, a mathematical calculation must first be made as to how such an extended body would act, assuming that it may be considered made up out of particles. This calculation is comparatively easy, given the distribution of the matter in space, provided we have a knowledge of what is called the "infinitesimal calculus," a branch of mathematics which Newton himself elaborated, partly for the purpose of which we are speaking. He succeeded in convincing himself that for all points outside a spherical portion of homogeneous matter the action was the same as it would be if all the matter were concentrated at the center, and that the same is true of any homogeneous shell inclosed between

two concentric spherical surfaces. He assumed, therefore, that, as a first approximation to the actual fact, any of the astronomical bodies could be treated mathematically as a particle concentrated at its center; he deduced the consequences, and then compared them with the observations which were available. Let me give a résumé of these. Copernicus had convinced most people that the sun and planets formed a system of which the former was the center around which the latter, including the earth, were moving in fixed orbits. In order to test this theory many new observations were made, especially by Tycho Brahe, whose observatory, established at Uraniberg on Huena, a small island belonging to Denmark, was equipped with the best instruments available at that time at the expense of King Ferdinand II of Denmark. These observations of Tycho Brahe's continued for many years, and were more accurate than any others made before that time. Towards the end of his life Tycho Brahe lived in Prague; and among his assistants was a young German named Johann Kep-

ler. After Tycho Brahe's death, the latter fell heir to his records and observations ; and he spent the rest of his life in studying them. After many fruitless attempts he succeeded in proving that all of Tycho Brahe's observations could be described by three simple statements, which have since been called "Kepler's Laws." If Newton's hypothesis as to the interaction of material bodies is correct, and if gravitation is the determining cause of the astronomical motions, then Kepler's laws must be mathematical consequences of this hypothesis. This Newton showed to be the case, a most wonderful achievement. He observed, further, that another test of his hypothesis was afforded by a comparison of the motion of the moon in its orbit around the earth and that of a body falling to the earth from a point close to it. If it were not for the gravitational action of the earth upon the moon, the latter would not move in its approximately circular orbit, but would fly off tangentially. If we know the radius of the moon's orbit and its period of revolution, we can deduce the dis-

tance it "falls in" towards the earth each unit of time; the distance an ordinary falling body close to the earth's surface falls toward it in a unit of time may be deduced from observations upon pendulums; in accordance with Newton's law the effect of gravity at the earth's surface should be 60 × 60, or 3600, times as great as that at the center of the moon, because the distance from the center of the earth to that of the moon is sixty times that from the center of the earth to its surface. Newton was able to find among astronomical records the figures he needed for the calculation of the moon's motion; and he used Huyghens's pendulum observations in order to deduce the gravitational force of the earth at a point on its surface. When he made his calculations he found his law verified to a high degree of accuracy.

Before continuing the discussion of the simple illustrations of gravitation, a few words should be added at this point in regard to the moon's motion. It is perfectly obvious, as Newton of course recognized, that the calculation

of the moon's motion is by no means a simple matter unless assumptions are made which correspond only approximately with fact. Thus, the orbit of the moon's motion is not circular, nor does the plane of this orbit keep a fixed position with reference to the earth ; the earth is not a sphere, nor is it homogeneous ; nor does it keep its shape fixed (owing to the motion of the tides). Owing to these and other reasons it is a matter of extraordinary difficulty to make exact calculations of the moon's motion. Newton himself introduced certain corrections into the simple theory ; so did Laplace and many later astronomers ; but it has only been within the past decade that, owing to the great skill and industry of Professor E. W. Brown, now of Yale University, we have had satisfactory means of calculation of this motion, and the result is what must be called perfect agreement with observation. It must be emphasized, moreover, that in none of this most extensive and exhaustive work has it been found necessary to modify in the slightest Newton's original hypothesis. (It is

only fair to add that Professor Newcomb, in a recalculation of all known facts referring to planetary motions, found that an extremely slight modification of the law, so far as distance was concerned, made certain facts agree better with the theory. This change, however, is not compatible with the motion of the moon, as Professor Brown has shown. Consequently some other explanation of the slight divergence between theory and observation in the motion of Mercury must be found.)

Now to return to the law of falling bodies, that is, to the question of weight. The connection between weight and the phenomenon of falling is of course obvious. The early philosophers, such as Aristotle, asserted as a self-evident proposition that the heavier a body was the faster must it fall. It is doubtful if to their minds or to those of their followers there was anything to be gained by trying the experiment. To them, all questions, whether referring to nature or not, were matters for intellectual discussion only. The idea of devising experiments by which to test hypoth-

eses concerning natural phenomena we owe in the main to Galileo. One of the first questions considered by him was that of falling bodies. He convinced himself by experiments and by simple reasoning that all bodies, no matter what their weight, should fall towards the earth at the same rate — excepting, of course, any differences introduced by the presence of the air, which might be marked if one body was large and light and the other small and heavy. As you may know, Galileo's thoughts on mechanics and his experiments performed upon falling bodies, projectiles, etc., were published in a series of "Discorsi," which were apparently conversations upon philosophical subjects between three friends. Of course there is never any difficulty in knowing which of these is voicing Galileo's own thoughts. His argument in regard to falling bodies is as follows: "If we have two bodies whose natural velocities (according to Aristotle's teaching) are different, it is clear that, if we join the two, the faster one must be retarded by the slower, and the slower accelerated by the

faster. Therefore, if it were true that a large stone fell with a velocity which we may call 8, and a small stone with a velocity 4, it would follow that, if the two were joined, the velocity would be less than 8. But the two together form a stone larger than the one which, falling by itself, had a velocity 8; and therefore the larger stone falls more slowly than the smaller, which is contrary to the hypothesis." The conclusion, then, is that the two stones, large and small, must fall with the same velocity. Galileo discussed also the effect of the presence of the air upon falling bodies, and says: "I believe that, if the resistance of the air were entirely removed, all bodies would fall with absolutely the same velocity." He also performed many experiments upon falling bodies; and it is perfectly clear that the logical argument concerning the subject, which I have quoted above, was not offered to convince himself of the equality of velocity of fall for all bodies; his observations had done that. Among his experiments he mentions allowing bodies of different weights to fall directly

and also down inclined planes, which have the result of making the effective force of gravity less, but do not introduce any other quality (except friction, which can be made very small). The most interesting of his experiments consisted in comparing the periods of oscillation of two pendulums consisting of fine threads of the same length, one carrying a cork sphere, the other a lead one. He noted that during a large number of swings — until in fact the motion finally died out — the periods were the same. He explained the fact that the vibrations of the cork pendulum die down more rapidly than those of the lead one as due to the comparative lightness of the cork and therefore the greater effect of the air upon it; but if the cork pendulum is given at the start a somewhat greater swing than the lead one, there will come a time when the amplitudes of the swings of the two pendulums are the same, and, since their periods are the same, they will then fall in the same time through paths which are identically the same.

One of his most famous experiments was

designed to call the attention of a large audience to the truth concerning falling bodies. He was living in Pisa at the time, and he had an assistant carry two cannon balls of different weight to the highest gallery of the famous Leaning Tower, while he remained at the bottom surrounded by a numerous company. At a given signal the assistant pushed the two balls off the ledge at the same instant; and those standing below saw them fall side by side and heard them strike the stone pavement as if with a single impact. We might suppose that every one who saw the falling balls and heard the simultaneous thud upon the ground would be convinced of the error of Aristotle's statement in regard to falling bodies; but quite the contrary was true. The spectators interpreted the observed fact by believing — what was a most obvious possibility to them — that the laws of nature had been perverted that day, and they attributed to Galileo the power of a magician, not of a philosopher. He himself, however, believed; and being convinced that all bodies, regardless of their

weight, fall alike, he determined to discover the law of motion of a falling body.

The most incidental observation proves that, as a body falls, it goes faster and faster, that is, the distance traversed is not proportional to the duration of time of fall; the velocity of fall, therefore, increases as time goes on and as the distance increases. In attempting to express the facts in some simple mathematical form, there are two simple hypotheses which we might make and which we could then test by comparing their deductions with observation. (It might be, of course, that neither hypothesis was satisfactory.) One is that the velocity increases uniformly with the *distance* of the fall; i.e., that, if the velocity at the end of a fall of one foot is a, at the end of two feet, it is $2a$, etc. Another is that the velocity increases uniformly with the time; that is, the velocity at the end of the second second is twice what it was at the end of the first, etc. Galileo discussed these two hypotheses and dismissed the first as leading to conclusions which were inconceivable. He,

therefore, concentrated his attention upon the second. He saw that it was impossible to test this hypothesis directly, because of the difficulty of measuring the velocity of a falling body at any instant of its fall; and, therefore, he resorted to what may be called indirect methods. He showed by mathematical reasoning that, if we assume as true the hypothesis that the velocity increases uniformly with the time, the distance traversed by the falling body must vary as the square of the time, i.e., if the distance passed over in the first second is x, that passed over at the end of two seconds is x^2, etc. Owing to the fact that a body falling vertically moves so very rapidly after the first few seconds that it would be with great difficulty that one could determine its exact position at any one instant, Galileo devised the most ingenious plan of having the body fall down an inclined plane instead of vertically. This modification simply dilutes gravity, as it were, making the force less in a definite ratio, depending upon the inclination which the plane makes with the vertical. With our mod-

ern methods of measuring time, it would be easy, indeed, to carry out this experiment of Galileo's; but he had at his disposal no watch, no clock; indeed, no timekeeping mechanism. He, therefore, was forced to use some other method of determining his time-intervals. What he actually did was to insert a fine tube into a small opening made in the bottom of a pail; this he filled with water, and he then arranged to open and close the tube and to catch the escaped water. This water he weighed on a balance; and he assumed that the quantity of water escaping was directly proportional to the time of opening, which is fairly true, so long as the level of the water in the large vessel does not change greatly. For his inclined plane he used a long wooden board along whose edge he made a straight smooth trough; and for his falling body he used a brass ball, accurately round and smoothly polished. Then, when he started the ball down the board he opened the tube leading into the pail of water, and allowed the water to escape until the ball passed some definite point on the board. He

in this manner compared the times of fall for the entire length of the board; one half of it, etc. (He also in other experiments set the board at different inclinations to the vertical.) The result deduced from all his observations was that the distance traversed by a falling body varies directly as the square of the time of fall; and that therefore the hypothesis that the velocity of a falling body increases uniformly with the time is verified. We call the time-rate of increase of velocity by the word "acceleration"; so the conclusion of all of Galileo's experiments is that the acceleration of a body falling vertically under the influence of gravity is a constant, the same for all bodies.

We may express this fact in the language of Newton by introducing his idea of mass. When a body of mass m receives under any circumstances an acceleration a, we say there is a force acting upon the body numerically equal to the product ma. So, if we call the acceleration of a body falling vertically by the symbol g, the force acting on it owing to

the presence of the earth equals the product mg. This, then, is the weight of that body.

Now, in accordance with Newton's hypothesis concerning the interaction of two bodies, the force acting upon any body near the earth's surface is proportional to the product of the mass of the body by that of the earth divided by the square of the distance of the body from the center of the earth. Owing to the enormous disparity between the radius of the earth and the size of a falling body and any height through which we ordinarily can let bodies fall, it is apparent that we may consider the distance from the center of the earth to all points of the body itself as being the same and as remaining unchanged during the motion. Therefore, Newton's law of gravitation says that the force acting on a falling body equals its mass multiplied by a quantity which is constant and the same for bodies of all sizes and materials. This is exactly what Galileo's experiments indicated; but, realizing the importance of the matter from the standpoint of the verification of his own hypothesis,

Newton determined to investigate the question anew. For this purpose he made use of pendulums which consisted of long threads supporting bobs of different materials. The law of vibration of a pendulum was known to Galileo, at least that part which states that the square of the period of oscillation varies as the length; i.e., if we double the length, the period becomes four times what it was; and he also made use, as we saw, of pendulums for the purpose of studying the laws of falling bodies. To Galileo the problem of a pendulum was what we may call a "kinematic" one, dealing with the motion of a body in a vertical circle, under a constant acceleration downwards; to Newton it was very different. Newton introduced into philosophy the ideas of quantity of matter or mass and of force; a pendulum, then, consists of a bob which is constrained to move in a vertical circle and which has a definite mass; and under the force which we call its "weight," this bob has a certain periodic motion. Naturally the period of the motion will depend upon how the bob re-

acts under the influence of the force; i.e., upon the opposition it offers to this force. Consequently we would conclude that the period of oscillation of a pendulum should in some way measure the ratio of the weight of a body to its mass. The exact formula was deduced by Newton, and is one of the most familiar in physics. It may suffice to say here that the formula proves that, if this ratio of weight to mass is constant; i.e., if the acceleration of a falling body is constant, then the period of oscillation of any one pendulum is the same for any amplitude of vibration so long as it is small compared with the length of the pendulum thread, and the square of the period of oscillation is proportional to the length of the pendulum. Newton accepted as proved by numerous observations that this formula was completely verified for any one pendulum; but he thought that the question of the identity of the ratio of weight to mass for all bodies required further investigation. The question, expressed differently, is this: If two bodies have the same weight, as tested by

a balance, do they also have the same mass, as tested by an impact experiment? or is it possible that different kinds of matter are affected differently by gravity, is there a specific quality in gravitation?

Newton, in order to dispose of this question, constructed two pendulums, each consisting of a thread eleven feet long and carrying a spherical box, in which could be placed different substances.[1] He made these last all having the same weight; and since they were inclosed in boxes of the same size and shape, the influence of the air upon the motion of the two pendulums was the same. He made use of the following substances: gold, silver, lead, glass, sand, common salt, wood, water, and wheat. His method was to allow the two pendulums to swing side by side, noting the agreement of their periods. If the acceleration is the same for the two bodies, the two pendulums ought to continue to swing together indefinitely. This Newton observed to take place; and he therefore concluded that the ratio of the weight

[1] *Principia*, book III, proposition VI.

and mass of all bodies is the same. Consequently this feature of his hypothesis concerning gravitation could be considered verified.

Newton estimated that the accuracy of his method of experimenting was such that any variation in the agreement of this gravity acceleration for different bodies greater than one part in one thousand would have been observed. We now know, however, that the agreement is much better than this. Bessel, the German astronomer, made a large number of pendulum observations,[1] using pendulums of different materials, and drew the conclusion from his observations that any difference which might exist was too minute to be observed by his method, which allowed a possible error of 1 part in 60,000.

We may say, then, that Newton's hypothesis has been verified so far as it states that gravitation is independent of the kind of matter constituting the attracting bodies, and so far as the law of distance is concerned, provided this distance is of an astronomical mag-

[1] *Mém. Berlin Akad.* (1830).

nitude. Two questions, however, arise: first, Does the law hold for radio-active bodies? second, Does it hold for small bodies at small distances apart?

Let us consider the latter question first. When one holds in his hand any ordinary body, say a pound weight, and realizes that the sensation of its weight which he experiences is that due to the action of the whole huge earth, he can easily believe that the force between two bodies, both of ordinary size, must be extraordinarily minute. This, indeed, is the case; and the utmost refinements of scientific measurement must be applied in order to make any accurate statement with reference to the force of gravitation between two bodies even of moderate dimensions. This has, however, been done; and various investigators, notably A. S. MacKenzie,[1] have studied the accuracy of Newton's law for small bodies. This observer has shown that for lead balls, 5 centimeters in diameter and for distances as small as 3 centimeters, the law holds within the lim-

[1] *Phys. Rev.* (1894).

its of experimental error. As to whether it holds for molecules, or for even small groups of molecules, no one can say. Lord Kelvin has shown that a law of the kind of Newton's, if it does hold for molecules, might account for the ordinary forces of cohesion in solids; but great difficulties would arise in applying the law to the molecules of a gas. As a matter of fact, whatever theory we have as to the ultimate cause of gravitational attraction, there are good reasons for there being a modification in the Newtonian law when we consider extremely small quantities of matter placed close together.

The second question raised in regard to gravitation was one concerning radio-active matter. Assuming that the gravity-acceleration of such a body is a constant, is this the same constant as for an ordinary piece of matter? This constant is the value of the weight of a body divided by that of its mass; and it is best determined by using the body as the bob of a pendulum, and measuring the period of oscillation for a thread of known length.

Suppose we were to make two pendulums, one having for its bob a definite weight of some radio-active matter, such as a uranium ore, the other having for its bob an exactly equal weight of some ordinary substance, such as lead; by means of each pendulum we could obtain the corresponding value of the gravity-acceleration. If both pendulums gave the same value for this, it would mean that the two bobs, which have equal weights, also have equal masses; on the other hand, if the two pendulums gave different values of the constant, it would mean that the two bodies of equal weight, as tested by a balance, had different masses. Believing part, at least, of the mass of a body to be due to the potential energy of the electric charges constituting its atoms, it is evident that, if this potential energy of a body contributes to its mass and not to its weight, — the latter being due to what we may call non-electric mass, — then two bodies having the same mass would not have the same weight — and *vice versa*, provided one had more potential energy than the other. This fact could be detected by pen-

dulum experiments. A radio-active body contains a large amount of potential energy as is shown by its transformation into the kinetic energy of the ejected alpha and beta particles. If this potential energy is in excess of that which is characteristic of the ordinary grouping of corpuscle and positive charge in ordinary matter, we can easily test the question as to whether or not there is this difference in the ratio of weight to mass. All that is necessary is to compare the vibrations of pendulums, one made of ordinary matter, the other of radio-active matter. This has been done by J. J. Thomson and more recently by L. Southerns,[1] one of his students. The latter used in his experiments pendulum bobs made of uranium oxide and of lead oxide, and was unable to detect the faintest difference in the two cases. His conclusion was that a difference in acceleration greater than 1 part in 200,000 cannot exist.

Taking into account all the phenomena of gravitation, we see that there is in the end

[1] *Proc. Roy. Soc.*, vol. LXXXIV, p. 325 (1911).

but one fact to explain, namely, why it is that two pieces of matter, if free to move, approach each other as stated in Newton's law. We have shown that the presence in atoms of positive and negative charges accounts for part at least of their mass; and we naturally ask if it is not possible to account for gravitation as due to these same charges in atoms.

The fundamental law of electrostatics is, as we have seen, that like charges repel each other and unlike charges attract; and experiments have proved that the force varies directly as the product of the charges and inversely as the square of the distance. So far as any electrical experiment can tell us, the force of attraction between two unlike charges is the same numerically as the force of repulsion between two charges having the same values as in the previous case but both being of the same kind. But electrical experiments admit of a test of this fact only to a certain degree of accuracy; and it is easily seen that, if the force of attraction is slightly greater than the corresponding one of repulsion,

there will be a resultant attraction between two bodies, each of which is electrically neutral.[1] The calculation of the difference between these two electric forces required to account for gravitation has been made by several men, making plausible hypotheses as to the values of the charges in the atoms; and all agree in the conclusion that the difference is so small that it could not be detected in any ordinary electrical experiment. We can see also that, if we imagine two atoms close together, the electrical forces between the different constituent charges will be sufficient to change the relative positions of the charges in the atom; and therefore the effective distance apart of the two atoms, the quantity which enters into the Newtonian law of gravitation, would be modified, and the law would cease to hold. The laws of electric force would still apply, but the various forces would combine into a single force in which the effect of the distance would not enter as the square of the

[1] See Sutherland, *Phil. Mag.*, vol. VIII, p. 685 (1904); J. J. Thomson, *Proc. Camb. Phil. Soc.*, vol. XV, p. 65 (1909).

distance between the two "centers" of the atoms.

A difficulty possibly arises in accepting this elementary explanation of gravitation when we consider the interval of time required for the production of a gravitational effect. All electric disturbances are propagated with a known finite velocity; while astronomers claim that gravitational disturbances travel with an infinite velocity. H. A. Lorentz[1] has shown, however, that this difficulty is avoided if we express our hypothesis in a slightly different manner, simply assuming that the electric disturbances produced by equal positive and negative charges are not exactly the opposite of each other.

It is thus seen that in attempting to explain gravitation we assume as our fundamental entities positive and negative electric charges, which we picture as distributed through the atoms of matter and which we assume have certain definite characteristic laws of interaction. The only progress we have made is in

[1] *Proc. Amsterdam Academy* (1900).

showing that the same mechanism will account for mass and for weight.[1]

The only other serious attempt to offer an explanation of gravitation was made by Le Sage. He showed how a motion of attraction between two bodies would result if there were streams of minute material particles, i.e., particles endowed with inertia, traversing space in all directions and if one made other incidental hypotheses. The objections to this theory, even when altered to suit our modern point of view, are numerous and apparently unsurmountable.

In speaking of the concepts of weight, mass, and force, and in discussing the history and development of these, it is not an easy matter to assign the credit for the ideas. There can be no doubt but that Newton was the first to introduce the definite concept of mass as an inherent property of matter whose quantity could be measured, and to define the word force as equal to the product of mass and ac-

[1] In this connection see papers by Einstein and Abraham in the *Physik. Zeitsch.* for 1912.

celeration; and it is clear that to him the word "weight" conveyed the idea of a force. To Galileo, on the other hand, "weight" meant at times the agency operative in falling bodies or in the tension of a string to which a hanging body was attached; while at other times it conveyed the idea of a property of the body itself, the "specific gravity" of the body being its weight divided by its volume. Galileo had a perfectly clear idea of the property of a body to which we give the name "mass" and referred to it as having a value given by its weight. He devotes one of his "Discourses" to the subject of impact, and describes experiments with the ordinary apparatus of two spherical bodies suspended by long threads. He notes that the determining quantity in impact is the product of the weight by the velocity; this he calls the "momentum." He says that every body which is subjected to an impact offers a twofold resistance to the change: one factor is "internal," confined to the body itself and measured by its weight; the other factor depends upon the magnitude of the

motion given the body — thus more effort is required to throw a stone one hundred paces than fifty. He analyzes the effect of such a sudden change, and says that the momentum of a body experiencing an impact is made up of an infinite number of parts each of which equals the product of the weight by a factor depending upon the motion; such momenta increase during the time of impact exactly as the velocity of a falling body increases, the body passing through all degrees of velocity from zero up to the final velocity. In another place he explains how an agency for producing motion, if acting for a long time, will cause a greater velocity. It is thus evident that Galileo had a perfectly clear idea as to the inertia of matter, the proper measure of an impulse, and the measure of a force. What he did not do was to define the mass of a body as a definite property independent of weight; and so he could not express his ideas in mathematical language.

IV

RADIATION; FORMATION OF MOLECULES; ELASTICITY

In a previous lecture the subject of radiant energy was mentioned; and the statement was made that this was energy emitted by charged particles making oscillations. The subject is so important that more detailed attention should be given it.

Bodies of all kinds are emitting this radiant energy, as may be shown by instruments of various types which are designed first to absorb the energy incident upon them, and then, owing to the addition of this energy, to indicate the fact by a change in some of their physical properties. Thus, some types of radiant energy will affect a photographic plate; some affect our eyes, in which case we speak of the radiation as being "luminous"; in other cases the temperature of the instrument will be raised, and this fact may be detected

by a change in the volume of some of its parts, by a change in its electrical properties, etc. An ideal instrument is one which would absorb completely all types of radiant energy and give an indication by which we could measure exactly the amount of the energy received. With our modern methods we can approximate fairly closely to this ideal instrument. When radiation is passed through a prism or is analyzed by some dispersive instrument, its energy is redistributed and spread out into what is called a "spectrum"; and the radiation leaving the prism in any definite direction is characterized by having a definite periodicity or wave-length. Thus the incident radiation is transformed into trains of waves, each train having a definite wave-length. The science of spectroscopy is the study of the analysis of the radiation from different sources. It is found that solids and liquids, with very few exceptions, emit a "continuous spectrum," i.e., we find in the spectrum of their radiation waves of all wave-lengths; whereas gases, when stimulated so as to produce radiation,

emit only isolated trains of waves, giving what is called a "discontinuous spectrum."

The obvious way in which one can explain these facts is to assume that inside the molecules there are centers of emission having definite periods. Such a center will produce waves of one definite wave-length so long as it itself is undisturbed; and consequently in the case of a gas made up of molecules all alike, or of groups of such molecules, there will be a radiation of such definite trains of waves in the intervals of time between the collisions of the molecules. If we picture an individual molecule, it collides with another molecule, then has a free path, then collides again, etc. During these free paths each vibrating emitting center is free to radiate its characteristic train of waves. But, if the molecules are as close together and as interconnected as they are in liquids and solids, there is no opportunity for this free emission; and consequently the spectrum is continuous. An analogy from the field of sound is furnished by a piano or a harp; if any one string is

plucked or struck, aerial waves of a definite frequency are emitted; but, if the strings are all connected by a cord, then, when any one string is struck, all the strings are set vibrating and so waves of all wave-lengths are emitted.

When the continuous spectrum emitted by a solid is examined by an instrument which measures the amounts of energy carried by the trains of waves of any definite wave-length, certain extremely interesting facts are brought to light. Let us define by a "black" body one which absorbs completely all radiation that may fall on it. It is not difficult to construct a body which practically satisfies this condition; and in fact a body coated with thick lamp black is fairly satisfactory. The radiation from such a body is of great theoretical importance and is the same for all black bodies at any given temperature. Many careful investigations[1] of its nature have been made; so that we now know to a high degree of ac-

[1] See article by Wien, "Theorie der Strahlung," *Encyk. Math. Wissensch.*, V^3, 282 (1909).

curacy the distribution of the energy in the spectrum of a black body at different temperatures. By analyzing these experimental results we are able to state in a mathematical formula the amount of energy carried by a train of waves of a definite wave-length in terms of this wave-length and the temperature. The formula which shows the best agreement with the facts of observation is one given some years ago by Planck.

It is seen, therefore, that in explaining the phenomena of radiation as connected with matter we must account for several facts:—

(1) The production of radiant energy by molecules.

(2) The emission of a discontinuous spectrum by any gas.

(3) The emission by a black body of a spectrum in which the energy is distributed continuously and according to a known law.

It has been shown by Larmor, Lorentz, and others that, whenever the velocity of a charged body is changed, it serves as the center of an emission of radiant energy. We can

apply this fact to the atoms constituting matter. They consist of positive and negative charges; and the latter of these, the corpuscles, are certainly in motion, as is shown by their escaping so easily from the atoms. The simplest type of motion we can attribute to the corpuscle is a uniform motion in a circle inside the atom; and here, although the speed of the motion may be constant, its direction is changing continuously, so there will be radiation as a consequence. Or, we can imagine two or more atoms forming a stable group, and can picture a corpuscle making revolutions along an orbit lying in the range of influence of the groups; here again there is a change of velocity, and therefore there will be radiation. Again, if we consider a system of atoms and corpuscles in which some corpuscles are leaving atoms and others are joining them, we have changes in the velocities of the corpuscles and consequently radiation. Other processes may be imagined; and there is no reason for not believing that all of them may take part in the radiation from bodies.

The first two processes would give rise to trains of waves of definite wave-length; the last would not; and therefore in the case of a gas we naturally imagine motions similar to the former as playing the most prominent part. Several serious difficulties arise however. One comes from the great frequency of vibration which is observed. Thus, the number of vibrations per second which is characteristic of those waves which produce in our eyes the sensation of blue is 75×10^{13}; and, if these are caused by the revolution of a corpuscle in an orbit, this enormous figure is the number of complete revolutions which the corpuscle must make each second. (If there are several corpuscles in an atom pursuing the same orbit, this figure is decreased; but it is still enormous.) Again, the spectrum of every known gas consists of numerous isolated trains of waves; and the vapor of iron emits at least fifteen thousand such separate and distinct trains. The spectra of many gases consist of trains of waves which are not distributed at random, but, on the contrary, exhibit striking

regularities. When their wave-lengths are measured and compared, it is seen that the numbers are connected by simple mathematical formulæ; and, further, when the spectra of similar gases are compared, the corresponding formulæ for them all are of the same form. These facts were first developed extensively by Kayser and Runge[1] and certainly have a most important bearing upon any molecular theories.

Other difficulties arise when we consider the Zeeman effect, to which brief reference has already been made. When a source of radiation is placed in an intense magnetic field, each train of waves is replaced by at least three, in some cases many more; so that the possibility of the corpuscle possessing these distinct periods — all of which coincide where there is no magnetic field — must be taken into account.

If an atom contains even a moderately large number of corpuscles, the radiation emitted by it is not that characteristic of the accelerations of the individual corpuscles, because

[1] See Kayser, *Handbuch der Spektroskopie.*

owing to the large number of oscillating parts there is an interaction between them; and that which finally emerges from the atom is a radiation characteristic of the average acceleration of the corpuscles. The same is true of the radiation produced by a molecule. Therefore any definite type of gaseous molecule would emit radiation all of one definite wave-length; and in the case of a gas whose spectrum has one thousand isolated trains of waves, we must assume the existence of this number of different molecules. These differences in molecules may be brought about in many ways;[1] e.g., there may be groups of two, three, etc.; some molecules may be charged, others uncharged, etc.

The type of radiation which we must have as the result of corpuscles leaving and returning to atoms deserves special attention, because this process is certainly going on in all solid bodies. In gases a state of dissociation and recombination of the atoms seems to be essential for the production of the characteristic radiation; and in this state we have violent accel-

[1] H. A. Wilson, *Phil. Mag.*, vol. XXIII, p. 660 (1912).

erations of charges. A definite amount of work is required to force a corpuscle out of an atom; and when it falls back again into an atom, it at first has an amount of kinetic energy equal to this; but as it gradually returns to its original condition inside the atom, this energy must be lost by a radiation process. Thus, each such recombination of corpuscle and atom will give rise to a pulse of radiant energy; and during a series of such recombinations there will be a series of such identical pulses emitted, each carrying equal amounts of energy. As Thomson has recently shown,[1] it is possible, by considering the radiation from solids to be of this nature, to calculate where in the range of wave-lengths these pulses will carry their maximum energy, and in this way to explain the origin of Roentgen rays. In order, however, to account for the periodicities observed with gases, the accelerations of the corpuscles must be analyzed much further.

We thus see that there is no great difficulty in picturing the processes of corpuscular mo-

[1] *Phil. Mag.*, vol. XXIII, p. 449 (1912).

tion which will account for discontinuous and continuous spectra; but, when the attempt is made to be more precise as to this motion, so as to deduce the exact laws for the distribution of energy in the spectrum, it is found that little progress can be made. Within recent years grave doubts have arisen as to whether we know the proper mathematical laws to apply to such minute particles as corpuscles or to the changes in the æther.

An interesting question arises in regard to the nature of the mode of propagation of the radiant energy, which has an important bearing upon the nature of the corpuscle, and therefore upon the constitution of the atom. Up to within very recent years every one has pictured the spreading out of the disturbance from any vibrating center as being the same in all directions; just as, when one drops a stone into a pool of water, a wave may be seen propagated out having a continuous circular front; or, when an organ pipe is blown, one may hear it from any direction, and the time required for the aerial wave to reach the

ear does not depend upon the direction. So we have supposed it must necessarily be in the case of light, and so it is, as far as our eyes or any instrument can detect. If there is a flame or any source of light, we can see it from all directions equally well. But quite recently Thomson has called attention to certain difficulties in the obvious interpretation of this fact, which is, of course, that there is a continuous wave-front to the radiant energy. One of these difficulties arises when we consider the phenomenon of ionization of a gas by Roentgen rays or by light. It has been proved that when radiation of short wave-length passes through a gas, some of the molecules are so disturbed that corpuscles are ejected. The number of molecules so ionized may be determined; and when the various facts are studied, it appears clearly that the ionization is much less than one would expect if the radiation had a continuous wave-front, i.e., if it had the same properties at all points over a given surface.[1]

[1] C. T. R. Wilson has shown (*Proc. Roy. Soc.*, vol. LXXXV, p. 285 (1911) ; vol. LXXXVII, p. 277 (1912)) this emission of

These facts and several others led Thomson to make the hypothesis that all radiant energy advances along lines or rays, which do not fill all the space through which the radiation is passing. Thus, if the energy is emitted from a point source, he imagines it being transmitted along lines drawn radially from this point. The radiation is thought to proceed from the corpuscles in the molecules, and to consist in transverse disturbances passing out along the tubes of force which form a permanent attachment to the corpuscles. As has been said before, Thomson pictures a tube of force as having the figure of a rod, and assigns a small

corpuscles by a most beautiful experiment, which merits description. He showed many years ago that, if there are minute charged particles in a damp atmosphere, the water vapor will condense on these as nuclei; and it has been known since Roentgen's original investigations on the radiation that bears his name that these rays ionize a gas, causing molecules to eject corpuscles; these in turn acting on other molecules also ionize them. In this last experiment by Wilson he filled a vessel with moist air, caused it to expand and thus become chilled so as to induce condensation of the water vapor, then within one twentieth of a second he allowed Roentgen radiation to enter the vessel. There was evidence of the formaation of minute drops along definite straight lines ; and photographs were taken showing the trains of drops.

number of them to each corpuscle. He attributes to them a real existence, and has shown how the mass of the corpuscles may be explained if we assign a certain amount of bound æther to each tube.

In order to have the wave-like disturbances pass along them we must assign them a definite elasticity; and in order for these waves to have the velocity characteristic of light, there must of course be a definite relation between the density of the bound æther and this elasticity. The passage of the energy along these tubes would not be unlike the passage of a transverse pulse along a tightly stretched string. Then, if we wish to picture, on this theory, the outward advance of a wave from a point source, we think of a spherical surface expanding outward, but active, so far as light, ionization, etc., are concerned, only at certain isolated points.

Faraday himself had this same view, for in one of his papers he said: "The view which I am so bold to put forward considers therefore radiations as a high species of vibration

in the lines of force which are known to connect particles and also masses together." Thomson quotes this in his book "Electricity and Matter," and adds: "The Faraday tubes stretching through the æther cannot be regarded as entirely filling it. They are rather to be looked upon as discrete threads embedded in a continuous æther, giving to the latter a fibrous structure; but if this is the case, then on the view we have taken of a wave of light the wave itself must have a structure; and the front of the wave, instead of being, as it were, uniformly illuminated, will be represented by a series of bright specks on a dark ground, the bright specks corresponding to the places where the Faraday tubes cut the wave front." It is only fair to add that Thomson's theory has found few supporters; and other explanations of the smallness of the ionization of gases by Roentgen rays may be given.

The mechanism of emission of radiation by molecules is not as difficult to imagine as are certain features of its absorption[1] by mole-

[1] See Schuster, *Theory of Optics*, 2d edition, chap. XI.

cules. As has been said, when radiant energy is absorbed by a body, the energy may be consumed in producing various effects; among these we may name vision, photographic action, fluorescence, etc.; but in the great majority of cases the final result of the absorption is rise in temperature. There can be no doubt but that this condition is due to an increased kinetic energy on the average for all the *molecules* of the absorbing body, where emphasis is laid upon the word molecules. Now the immediate absorption process must be one concerned with corpuscles; the corpuscles of an atom cause the radiation, those of another must absorb it. There can be no doubt but that this absorption process must be dependent upon resonance. The fact that a corpuscular system can and does under certain conditions emit radiation of a definite periodicity proves that, if this radiation were to fall upon another system capable of emitting radiation of the same periodicity, this latter system will absorb a portion of the incident radiation. (Just as, if we have two tuning-forks which have the same fre-

quency, and, if one of the forks is set vibrating, the aerial waves emitted by it will fall upon the second fork and being absorbed by the latter will set it in vibration.) If radiation having any definite periodicity falls upon any corpuscle, a certain amount of energy will be absorbed by the latter, regardless of its own condition or its own periodicity; but the amount varies greatly. In any case, however, the beginning of the process of absorption must be this increase in kinetic energy of the corpuscles of the absorbing molecules. The question then arises as to how this energy becomes distributed among the molecules themselves, because, as we have said, rise in temperature requires this. It must be shown how, at the moment of collision between two molecules, one having corpuscles which have gained energy by absorption, there is a transformation of this energy, so that the two molecules separate with greater velocities than they would have had if there were not this absorbed energy. The exact process by which this takes place is not clear; the initial

and final facts are, however, perfectly definite.[1]

This transformation of the radiant energy which has been absorbed by corpuscular systems into the irregular kinetic energy of the molecules, which is manifest to our senses by the production of some heat-effect, such as rise in temperature, is not, of course, the only way in which such absorbed energy is spent. There is a large class of bodies which do not show any marked change of temperature when there is absorption, but emit an equivalent amount of radiant energy themselves. In some cases this energy is emitted only during the actual time of the absorption of the incident energy; such bodies are called "fluorescent": other bodies continue to emit energy for some time after the incident energy is shut off; such are called "phosphorescent." The facts with reference to these phenomena have been investigated

[1] J. H. Jeans, in his *Dynamical Theory of Gases* (Cambridge, 1904), discusses some of the features of this problem with great success, and has shown how many of the difficulties in the study of the redistribution of the energy may be solved.

with great care; but no theory to account for them which is really satisfactory has been advanced thus far. For purposes of helping our imaginations, it is found useful to think of a molecule of a fluorescing or phosphorescing body as consisting of two distinct parts, the function of one being to absorb the radiant energy, that of the other, to emit the characteristic radiation. These two parts are thought of as so connected that, when the energy of the first part increases to a certain amount, there is a stimulation of the second part; and, as a matter of fact, there must be several modes of connection between the two parts. By far the most important investigation of fluorescence is that by Professor R. W. Wood, of the Johns Hopkins University, who had studied this phenomenon in sodium vapor, mercury, and other gases. One of the most interesting facts discovered by him was the striking effect upon the phenomena of the addition to the fluorescing gas of a small quantity of some neutral gas. This is not the place, however, to go into any detailed description of these beautiful experiments.

Another most important property of matter is that referring to the formation of molecules. This is the field of the science of chemistry. The fundamental physical entities are the corpuscle and the corresponding positive charge; or, if one prefers, the corpuscle and the neutral atom. These atoms can combine in definite groups, which have an existence as such; of these there are two kinds, called molecules and ions. We use the word molecule to express a minute part of those forms of matter which we can isolate from other bodies, e.g., copper, hydrogen gas, etc. When salts or acids are placed in solution, e.g., when common sulphuric acid is poured into water, a certain proportion of the acid molecules are broken up into smaller parts in the act of going into solution; it is of course a question of the relative potential energy of these parts and the original molecules. These fragments of the molecules of the salt or acid are always electrically charged and are called ions, for reasons which are clear to any one familiar with the phenomena of electrolysis.

We picture these ions as moving to and fro in the liquid, recombining to form molecules, then dissociating again, etc. Both the molecules and the ions are in motion through the body of the liquid; and, when a steady state is reached, as many molecules are dissociated in any small interval of time as are formed by recombination. Such a state is what we call "statistical equilibrium." When an ion is formed by the resolution of a molecule, it does not remain distinct, but collects around itself a number of the neutral molecules of the liquid; so that the actual moving part is a relatively large body, made up mostly of neutral molecules, but controlled electrically by the charged fragment of a dissociated molecule. These ions cannot be removed as such from the liquid through which they are moving, and therefore are not molecules. (We can also, as has been said repeatedly, ionize a gas, i.e., make it an electric conductor; but in this case the ions are a corpuscle and the positive charged remnant of a molecule, each with an atmosphere of the

gaseous molecules attached unless the gas is greatly rarified.)

One of the ions formed from sulphuric acid is SO_4, a group formed of one atom of sulphur and four of oxygen. This group cannot exist as such, uncharged and taken out of the water; in other words it cannot become a molecule. Another ion formed from sulphuric acid is a charged hydrogen atom; but, in order to obtain hydrogen *gas*, this atom must lose its charge and be combined with another uncharged hydrogen atom; or we may consider it as retaining its charge and combining with another hydrogen atom having an opposite charge; for hydrogen gas consists of hydrogen molecules, each of which is electrically neutral and consists of two hydrogen atoms. The sulphuric acid molecule is electrically neutral and is a combination of two atoms of hydrogen, one of sulphur and four of oxygen. Similarly, all molecules are neutral and consist of combinations of atoms; and so any theory of the formation of molecules must be based upon the two fundamental facts:

(1) that however the individual atoms may be charged there must be equal amounts of positive and negative charges; and (2) that the forces holding the parts together must be those which produce a condition of stable equilibrium under existing conditions of temperature, pressure, and environment.

The idea that molecules consist of parts held together by electrical forces is almost as old as the science of chemistry; but no success was had in offering a satisfactory explanation of the diverse facts until J. J. Thomson made his epoch-making suggestion in regard to the nature of an atom. We shall take up presently the details of his hypothesis; but for the purposes at hand we can picture the atom, as we have been doing for some time, as consisting of a positive charge occupying a continuous central nucleus and an equal negative charge consisting of discrete corpuscles. We can think of the corpuscles as existing outside the positive electrification and connected with it by tubes of force, or as distributed through the volume occupied by the

positive charge. An important point to emphasize is that a definite volume in space cannot be thought of as being occupied by one atom to the exclusion of another; because, an atom being defined by its mass, and mass at least in part being conditioned by the presence of potential energy, we can have the potential energy in any volume altered by the addition of more energy. If we picture, then, two atoms coming close together, we can imagine the passage of one corpuscle from one atom to the other; this would result in one atom becoming negatively charged, the other positively; and, owing to the force of attraction between two unlike electrical charges, these two atoms might be held together and thus form a molecule. The fundamental part of the theory, and the one requiring explanation, is the passage of the corpuscle from one atom to another. Why should it not remain associated with its own atom? We can easily offer an explanation in terms of potential energy. It is a general statement of fact that motions and changes in nature take place

of themselves, if they occur at all, in such a manner that the potential energy of the whole system becomes less. Thus, as was explained in the first lecture, a heavy body falls towards the earth if left to itself, and the potential energy decreases; a compressed spring or bent bow, if released, returns to its "natural" condition, the potential energy of the strain vanishing, etc. There is of course in each atom a definite amount of potential energy, depending upon the number of corpuscles and their arrangement, and the amount of such energy will vary for atoms of different elements. Then, in accounting for the formation of a molecule made up of two different atoms, e.g., one of hydrogen and one of chlorine, which combine to form a molecule of hydrochloric acid, we might offer an explanation by saying that the configuration of the two different atoms is such that although the removal of the corpuscle from one atom might require work, this is offset and more by the loss in potential energy owing to its addition to the other, so that on the whole the potential energy is de-

creased. But at first sight this explanation would not apply to two identical atoms, e.g., two hydrogen atoms. Yet we can see that there is no reason to believe that the change in the potential energy due to the removal of a corpuscle is equal to that produced by the addition of one to the same atom. (If we add a pint of water to a pitcher already nearly full, some will run over; while, if we remove a pint, no such catastrophe will occur.) Thus the reason for the formation of molecules is reduced to a general principle relating to potential energy in all its forms; but it must be remembered that this is in the end little more than a description; not an explanation.

The theory given above assumes that each of the atoms making up a molecule is itself electrically charged; this is not essential. All that it is necessary to assume is: (1) that there are electric forces between two or more atoms; and (2) that the potential energy of the system is decreased by the atoms arranging themselves in definite groups. For example, each atom in a molecule may act like an electric

doublet, consisting of two equal positive and negative charges at a minute distance apart. Valency, etc., can be explained on this theory as well as on the former.

An idea which has played an important part in chemistry and especially in electro-chemistry is that of "valency." Experiments have shown that in the composition of stable compounds we may consider each atom as having a small definite number of modes of attachment to other atoms. For instance, the hydrogen atom has but one, i.e., if it is attached to any other atom, it cannot be attached to an additional one at the same time; the chlorine atom has also but one; the oxygen atom has two; the carbon atom has four, etc. Thus stable molecules are H_2 consisting of two atoms of hydrogen; H_2O consisting of one atom of oxygen and two of hydrogen; HCl, consisting of one atom of hydrogen and one of chlorine; CH_4; etc. Expressed in a different way, we may say that, to form a stable molecule by the combination of hydrogen atoms with one atom of any element a definite

number of the former is required; this number is called the "valency" of the element which furnishes the single atom. For experiments prove that in the formation of *any* stable molecule each atom retains its valence; so that an atom having a valency of two, for instance, is combined with two atoms each having a valency of one, or with a single atom having a valency two. Expressed in this way we say that hydrogen has the valency one; so has chlorine; oxygen has the valency two; carbon, four, etc.[1]

It is true that hydrogen and oxygen unite to form a compound containing an equal number of atoms of each; but it is not as stable as the molecule of water. The same is true of many other atoms; such compounds are called "unsaturated." It is well known also that an atom may have a definite valence as shown by a large number of compounds, but

[1] The "hydroxyl group" OH, consisting of one atom of oxygen and one of hydrogen, has a valency one; and the facts concerning the valency of any atom are shown most clearly by the number of such groups which combine with the atom in question to form a stable molecule.

that in compounds of a different character it may have quite a different valence. These facts must be explained by any theory of the constitution of the atom, if it is to be considered satisfactory.

Since we think of molecules being formed by the grouping of atoms, each of which has lost or gained corpuscles, it is evident that the facts of valency can be explained by saying that any definite atom can lose or gain one, two, etc., corpuscles and be stable; and that an element whose valency is one is such that any of its atoms can lose (or gain) one corpuscle and be stable, but would be unstable if it lost (or gained) two; an element whose valency is two is one whose atoms might lose (or gain) one corpuscle and be stable, but whose stability would be greater if they lost (or gained) two. We can learn whether an atom in general loses a corpuscle or gains one by experiments upon the ions formed in the solution of salts and acids. Thus it is known that a hydrogen atom as a rule loses a corpuscle, while an oxygen atom gains two. So,

in the molecule of water vapor, H_2O, we think of a compound of two hydrogen atoms, each of which has lost a corpuscle, and an oxygen atom which has gained the two. Similarly in the molecule of copper oxide, CuO, we think of a copper atom which has lost two corpuscles and an oxygen atom which has gained them. (Other compounds of hydrogen and oxygen and of copper and oxygen are known, as I have said, but they are not as stable as those mentioned.) Thus, we think of the atoms of each element having the possibility of losing or of gaining one, two, or more corpuscles; but we see that these atoms after they have lost or gained a definite number of corpuscles are more stable than if they had lost or gained a different number. Thus, a hydrogen atom, whose valence is one, will be stable in a molecule where it has lost but one corpuscle; an oxygen atom, whose valence is two, is stable if it has gained one corpuscle, but much more so if it has gained two, etc. An element whose atoms remain stable after the removal of one or more corpuscles is called

"electro-positive"; while one whose atoms remain stable after the addition of one or more corpuscles is called "electro-negative." There are some elements whose atoms do not form molecules with other atoms, for instance, helium, argon, etc. We picture then these atoms as being at the same time molecules, and as not being able to remain charged permanently; i.e., if one of them loses a corpuscle, it will by virtue of its electric force attract to itself another, becoming neutral again.

We have spoken so far as if every molecule might be considered as made up of discrete atomic parts, each part charged, but the total molecular charge being zero. This would imply that, if we were to disrupt a gaseous molecule into its atoms, or into atomic groups, as may be done by the impact of the canal rays in a vacuum tube, we would find each atom or each group charged and we would certainly expect to find each particular kind of atom always charged the same way; e.g., a hydrogen atom always positive, a chlorine atom always negative, etc. As a matter of fact this is not

true; when a large number of gaseous molecules are disrupted, each into two parts, these seem to have on the average the same electrical properties.[1] This probably means that each of the parts, e.g., each atom, contains equal amounts of positive and negative electricity, forming a "doublet." This would not exert any force at a distance; but two such doublets, if brought close together in a definite way, would attract each other, and thus two such parts might form a molecule. In order to formulate the condition for the formation of a molecule with this point of view we may use the concept of potential energy as we have before.

The other general properties of matter of which we have not yet spoken are those which refer specially to the size and shape of bodies. We distinguish between solids, liquids, and gases; between bodies which are elastic, like steel, and those which are plastic, like putty; between fluids which are viscous, like pitch, and those which are limpid, like water, etc.

[1] J. J. Thomson, *Phil. Mag.*, vol. XXIV, p. 209 (1912).

Some of these properties we can explain as being direct consequences of the fact that molecules have mass. For instance, if we have a gas enclosed in a cylinder which is fitted with a piston, and if we push in the piston so as to compress the gas and then withdraw it to its original position, the gas expands again, returning to its previous volume; so we say that a gas is perfectly elastic. (If we cannot see into the interior of the cylinder, we might think when we were pushing in the piston that we were compressing a spiral coiled spring.) This property of a gas follows at once from the molecular motions in the gas. The molecules are moving at random in all possible directions, impinging on the piston and therefore requiring a force to be applied to it to keep it from being pushed outwards; further, when the piston is withdrawn, leaving an empty space behind it, of course the moving molecules instantly penetrate it. The viscosity of a fluid is indicated by the slowness with which it flows; it is due to a type of friction. As the fluid moves through a tube or pipe, the layer

in contact with the wall remains practically at rest; the next layer moves slowly, the next more rapidly, etc.; the fastest portion of the fluid being that close to the axis. Thus we have the problem of considering two layers moving in the same direction, but with different velocities. We all know, from the illustrations of the flowing of water and gas in our houses, that in order to maintain this flow we must have a difference in pressure at the two ends of the pipe, thus producing a force which makes the flow. In order to explain the phenomenon we must show that in the case of the two layers moving with different velocities the one which has the less velocity exerts a backward force on the other so that the motion of the latter would cease were it not for the pressure. It is a very simple matter to show that this retarding force is an immediate consequence of the wandering or diffusion of molecules across the imaginary surface between the two contiguous layers. Others of these specific properties of bodies may be explained in a similar manner; but the number of such

is limited. In the main we are driven simply to describe the phenomena, introducing perhaps the word "force," which of course is in no sense an explanation. Thus we think of a solid as made up of molecules closely packed together and acted on by such forces as prevent in general any individual from wandering far away; it will vibrate about a definite central position, impinge on other molecules, etc. If the solid is deformed very slightly, e.g., by compression, bending, twisting, these intramolecular forces are so changed — or new ones of such a nature arise — that, if the deforming agency is removed, the solid returns to its original condition. Solids differ greatly in regard to the magnitude of the original molecular forces, and the consequent chance that a molecule has, owing to its velocity, of escaping from the surface of the solid. Thus, if two soft solids such as gold and lead are placed in contact, there is a progressive diffusion of gold into the lead; the molecules intermingle. Again, solids differ greatly in regard to the amount of deformation they can undergo and

still be able to return to their original condition; in some cases when this limit is reached, the molecules are moved into other positions of equilibrium, e.g., lead, putty; in others the configuration of the molecules is so broken up that the solid is permanently weakened, and the solid is more easily fractured, e.g., brass, steel, etc. So I could continue, almost indefinitely, describing the various types of solids and liquids; but little would be gained from the standpoint of knowledge. No serious attempt has been made to advance hypotheses sufficient to account for these molecular forces,[1] the truth being that with our fundamental ideas of the structure of an atom and of a molecule it is not at all difficult to see, in a general way, how these forces arise; and the differences in the structure of different molecules, as shown by their varied properties, indicate the reasons for the different elastic forces. When we say that experiments prove that a molecule is electrically neutral, we mean that there are in it equal amounts of positive

[1] See Mills, *Phil. Mag.*, vol. XXIV, p. 483 (1912).

and negative charges, as shown by their action at points far distant from the molecule, in comparison with the size of the molecule itself. But unless the centres of action of the two charges agree exactly, and unless the two charges themselves are exactly equal, this neutrality of action will cease to exist for points as near to a molecule as is another one. You can see, therefore, the elements of a theory which has sufficient flexibility to explain almost any type of molecular force.

I cannot leave this subject of the general properties of the size and shape of bodies without referring to a most interesting conclusion drawn by Fitzgerald and by Lorentz from certain observations made in regard to bodies which are moving rapidly through space.[1] Michelson and Morley performed many years ago a series of experiments with the object of studying the effect, if any, upon the periodicity of a beam of light of altering the direction of the beam with reference to the motion

[1] See Whittaker, *History of the Theories of the Æther*, p. 432.

through space of the source emitting the light. Their method was to take advantage of the motion of the earth itself. A source of light in any laboratory is moving rapidly; and by means of mirrors one can throw a beam of light in the direction of motion or in a direction perpendicular to this. The experiments of Michelson and Morley have no direct bearing upon the constitution of matter, or, at least, an investigation of this question was not their purpose. But, using the accepted hypotheses of physics and applying to them simple mathematical principles, — which, of course, add nothing of themselves, — Fitzgerald and Lorentz showed that the immediate consequence of the investigation was to prove that, when any body is moved in space, its dimensions are changed along all lines in the body drawn parallel to the motion; namely, these lines are all shortened. So a body having a spherical figure assumes a spheroidal one owing to its motion, its shortest dimension being in the direction of motion; a rod is shortened if moved lengthwise, but the length is unaffected if it is moved

sidewise, etc. Of course, these changes in dimension are extraordinarily minute unless the velocity is very great. There can be no serious attempt to explain this change in dimensions, this crowding together of the molecules — perhaps accompanied by a change in figure of the molecule itself, until we can formulate the law for the forces holding the molecules themselves together.

It is only fair to state here that we can make other hypotheses on which to base our mathematical structure and so deduce formulæ which may be compared with observations of nature; and, if we adopt those of Einstein, this question of the "Fitzgerald-Lorentz deformation" of matter does not arise. In the concluding lecture of this course I shall return to this point.

V

PROPERTIES OF METALS: THERMIONICS; MAGNETISM

In the four preceding lectures I have discussed what we may call the universal properties of matter—mass and weight, emission of radiation and chemical actions, properties common to all bodies; and I have shown how far they may be explained as due to the existence of electric charges. In this lecture, I wish to consider certain special properties of bodies, so far as we can make definite classifications.

In speaking of the simple phenomena of electricity, I defined the words "conductor" and "non-conductor." When we charge two bodies by bringing them together and then separating them, we find that in some cases the attractive power is limited to the surface of contact, while in others it is manifest over the entire surface of the body; the latter class of bodies are called "conductors"; the former,

"non-conductors." This fact of experiment, enabling us to divide all known bodies into two groups, evidently points to a simple fundamental property of matter.

We picture an atom of any kind as consisting of a certain amount of positive charge and an equal amount of negative charge in the form of corpuscles. We can easily imagine bodies electrically neutral but differing essentially in the manner by which this neutrality is maintained. One type of body might be composed of molecules each individual of which is neutral; the atoms constituting the molecule are charged, but there are equal amounts of positive and negative charges. Another type might be one in which a certain proportion of the molecules have allowed a corpuscle to escape into the intra-molecular spaces, so that each such molecule is positively charged; but, of course, to an observer on the outside of such a body there would be no evidence of a charge, as the negative corpuscles and the positive molecules are so close together as to neutralize each other's action outside the body.

The forces of attraction between corpuscles and charged molecules would naturally draw the former back into the molecules; but, if this property of matter is a natural one, like the formation of ions in an electrolytic solution, we must assume that as fast as corpuscles recombine with charged molecules, other molecules emit new corpuscles; so that the condition of the body on the whole is one of statistical equilibrium. There are many conditions like this in nature, where, on a large scale, everything is apparently steady, but really, if we take a minute enough view of the phenomenon, there is movement and change. Thus, if we put a vessel of water under a bell-jar, the water will evaporate; but, after a short while, we shall notice that the volume of water ceases to decrease; apparently, the process of evaporation has ceased. But this is not true. The evaporation continues; but its effect is neutralized by the condensation of the aqueous vapor on the surface of the water; so, on the whole, there is no gain or loss in volume of the water; for every molecule which passes

out of the water surface into the space above one descends from the latter and is enmeshed at the surface. This type of equilibrium must exist then in those bodies whose molecules spontaneously emit corpuscles. In the case of a solid body the molecules stay comparatively fixed in position and the corpuscles move to and fro at random in the space between the former. Some corpuscles will certainly escape; but, as they do, the body itself becomes charged positively, thus making it more difficult for other corpuscles to leave the surface.

When two bodies are brought into contact so as to touch over any surface, it is an experimental fact that when separated the bodies are charged, one positive, the other negative, the two amounts being equal. This means that the molecules of one of the bodies at the surface of contact have lost corpuscles, which have passed across to the contiguous molecules of the other body. (This is simply a statement of fact, a description, not an explanation.) Let us now see what we should expect to take place if the body losing the corpuscles is one

of the second type as described above, that is, if it is made up of molecules in kinetic equilibrium with corpuscles. In this experiment of which we are speaking it has lost a certain number of corpuscles out through the surface of contact with the other body, and then has been separated from the latter. Since the body has lost corpuscles, there will be a number of charged molecules left uncompensated; so, as the random motions of the corpuscles continue, they will serve to neutralize molecules in the *interior* of the body, leaving the charged molecules distributed at random over the surface. Similarly, let us suppose that in the charging process this body has gained corpuscles. Since before the contact with the second body it had sufficient corpuscles moving throughout the molecular spaces to neutralize the charged molecules present, these additional corpuscles are not needed for this neutralizing action, and since we have assumed a perfectly random motion of the corpuscles, the excess of these will be distributed over the surface of the body. Thus, in both cases of

charging, the corpuscles or the charged molecules are distributed over the entire surface of the body; regardless of where or how large the surface of contact with the other body was. Such a body as this, then, is what we have called a "conductor."

If, on the other hand, the body which has gained or lost the corpuscles is one which has no free corpuscles, but consists of neutral molecules, there is no process by which the molecules modified by the contact can be redistributed through or over the body, and therefore the charged surfaces alone have charges. Consequently, the latter kind of body is a non-conductor.

The fundamental fact that there is this passage of corpuscles across the contact-surface between two bodies I have not attempted to explain. It is easy enough to describe the phenomenon in other words: thus we may say that, whenever there are two different molecules brought close together, the constituent corpuscles are under the action of two forces, one tending to attract them to one molecule,

the other, to the second molecule; the corpuscle will therefore move under the action of the greater force and attach itself to the corresponding molecule. This is equivalent to saying that any definite molecule may be considered as having a specific attraction for corpuscles. This, however, is only a description and is not to be thought of as an explanation. When we come to describe the internal constitution of atoms, we must include in the conditions to be satisfied by our hypothetical atom that of allowing this specific attraction to exist. In other words, in picturing the essential differences between molecules of different substances, this specific attraction of corpuscles must be an obvious consequence of our hypotheses.

This conception of a conductor, given above, which may be considered as suggested by the fundamental property of a conductor so far as charging by contact is concerned, is supported by many other known facts concerning conductors. Let us consider briefly a few of these.

If I hold one end of a short metal rod in my hand and place the other in a hot flame, I am soon conscious of the fact that the end in my hand is becoming hot. In other words, if the temperature of one end of a metal rod is maintained very hot, the temperature of the other parts of the rod is also raised, the points nearer the hot end having the higher temperature. This fact is true of all bodies to a certain extent; but experiments show that in the case of non-conductors, such as wood, sulphur, quartz, etc., the effect is minute in comparison with what it is in metals, which are conductors. In ordinary language we say, then, that electrical conductors are good "heat conductors." Experiments further show that this so-called "conductivity for heat" varies greatly in different metals, and that for any one metal it differs when different temperatures are used.

The best known property of a conductor is exhibited with reference to an electric current. I have spoken very hurriedly of this phenomenon in a previous lecture; but it now demands

a more detailed description. If we charge any two conductors, say, two metal plates or two metal spheres, one positively and the other negatively, and then join them by a metal rod or wire, we find that many changes take place: the charges on the two conductors will be altered (and in a special case may disappear); the temperature of the connecting rod or wire is raised; and, while the change is going on, there is a magnetic field near the rod or wire, i.e., if a magnetic needle is suspended nearby, it will by its motions indicate that it is under the action of a new force. All these actions constitute the phenomenon which we describe by saying there is an "electric current in the rod or wire." In the experiment described the effects are most transient; the time required for the complete change is extremely small. But owing to the discoveries of Volta, Faraday and Seebeck we have means of maintaining the action for as long a time as we wish. Without going into the full explanation of the mechanism, I can describe one at least of the methods used for this purpose. Volta showed that, if one dipped

a rod of zinc and another of copper into a vessel of dilute sulphuric acid, and joined by a metal wire the two emerging ends of the rods, there was a continuous electric current in the wire (and also through the two metal rods and dilute acid): the temperature of the wire is raised and there is a magnetic field around it. Volta himself did not recognize these two effects; but that fact is unessential for our purposes. The heating effect of a current is shown most obviously by the ordinary incandescent electric lamp; and the magnetic effect is responsible for the functions of the telegraph, the telephone, the electric call-bell, and a hundred instruments in daily use. This electric conductivity of a conductor, then, is a most important property; and experiments have shown that it differs greatly for different bodies and for the same body at different temperatures.

Other properties of a conductor will be described presently; but let us confine our attention now to these two: conductivity for heat and for electric currents. Before offering any

explanation of them, I must stop to state what is meant by temperature. There is no word, I think, in our language which is so much used to conceal ignorance as "heat," and no word about which there is so much confusion of ideas as "temperature." Yet, if we confine our use of these words to the knowledge that comes from daily experiences, there need not be the least difficulty. I shall avoid the use of the word "heat" and so shall not discuss it, much as I should like to; but I must speak of temperature. We use the words "hot" and "cold" to describe our sensations when we hold our hands near a flame or near a block of ice; and we say that the former has the "higher temperature."

By choosing as an instrument some material body and selecting some property of that body which changes as the temperature is changed, we can make a "thermometer"; and then, by defining a scale, e.g., the Centigrade one, we can give numbers to any thermal conditions. When we investigate the physical differences between a hot body and a cold

one, or when we learn by what physical processes we can make a body hotter, we find that its temperature is determined by the average kinetic energy of translation of the molecules of the body, neglecting any regular systematic motion. (Thus, if an elastic body, such as a tuning-fork, is vibrating, or if wave disturbances are propagated along a stretched cord, these molecular motions are not included in the kinetic energy which determines temperature.) A good illustration of this is offered by a gas enclosed in a cylinder fitted with a piston. If we push the piston in, so as to compress the gas, the temperature of the latter is raised, as any one knows who has blown up a bicycle or automobile tire with a hand-compression pump. As we know, the molecules of the gas are in rapid motion, bounding back and forward; if we picture to ourselves a molecule as it strikes the piston, it will be reflected, keeping its speed unchanged if the piston is at rest; but, if at the instant when the molecule strikes the piston, the latter is pushed in, it will give an additional speed to the molecule,

and therefore the kinetic energy will be increased. This increased kinetic energy of the molecules appeals to our senses as a rise in temperature. Similarly, if the gas expands, pushing out the piston, it does work, and so the average kinetic energy of the molecules decreases; and we all know that, when a gas does expand, its temperature falls, e.g., as shown in the formation of clouds. Owing to its continuous series of impacts the velocity of a molecule of a gas is changing every instant; but if the number of molecules is sufficiently large, the average kinetic energy of all the molecules will remain unchanged unless some work is done on the gas, e.g., compression; or unless the gas itself does some work, e.g., by expanding. Thus we see that, if by any process the average kinetic energy of translation is varied, so is the temperature. Lord Kelvin many years ago called attention to the fact that it was possible to define temperature, i.e., describe a mode of giving a number to this property of a body, in such a manner as would be entirely

independent of the thermometric substance used in the measuring instrument. This he very properly called the "absolute" temperature system. He also showed that for all practical purposes this system agreed with the system one would have if as the thermometer we used a bulb containing a gas such as hydrogen or nitrogen and measured the change in volume of the gas, the pressure on it being kept constant as the temperature changed. He further proved that with matter as known to us there is a definite minimum temperature, lower than which it is impossible to reduce a body; this is called "absolute zero"; and for convenience this is taken as the starting-point of the absolute scale. Thus, when we speak of "300 degrees absolute," we mean a temperature 300 degrees on the absolute scale above absolute zero. (If the Centigrade scale is used, this 300 degrees absolute is equivalent to 27 degrees above the temperature of melting ice.)

By applying our ordinary principles of mechanics to a gas, as indicated in a previous lecture, it is not difficult to prove that in order

to make the properties of the theoretical gas agree with those of actual gases, we must assume that the average kinetic energy of translation of the molecules of a gas is proportional to the absolute temperature, i.e., the former equals the latter multiplied by a constant number, this number being the same for all gases. (This fact of the average kinetic energy of the molecules being equal to a constant multiplied by the absolute temperature is also believed to be true of solids and liquids, the constant being the same as for a gas.)

Now to return to our mental picture of a conductor as being a body in which there is a state of statistical equilibrium between the corpuscles moving freely between the molecules and the comparatively stationary molecules.[1] The conditions affecting the motions of these corpuscles are in some respects like those which apply to the molecules of the gas; and Drude made the bold assumption that we may apply to these corpuscles the general gas

[1] See Thomson, *Corpuscular Theory of Matter*. Lorentz, *The Theory of Electrons*, Leipzig (1909). Richardson, *Phil. Mag.* (1912).

law connecting temperature and average kinetic energy, i.e., that the average kinetic energy of the corpuscles is equal to the absolute temperature of the metal multiplied by the same constant as applies to gases. Further, the temperature of these corpuscles in any small portion of the conductor will be the same as that of the molecules themselves in that portion. (We can compare the condition of the free corpuscles in the space between the molecules with that of the molecules of air in the empty spaces in a porous body. The air assumes the same temperature as the solid walls owing to repeated impacts.)

We can at once see how it is possible, not simply to offer a general explanation of the phenomena of both heat- and electrical conductivity, but also to apply to them mathematical analysis. Consider first the heat-phenomenon. If the temperature of one end of a metal rod is raised, the average kinetic energy both of the corpuscles and of the molecules in that end is increased; but by an equilibrating process of diffusion between these corpuscles

and those adjoining them farther down the rod the kinetic energy of the latter is also increased. For the molecules at any portion of the rod to be in equilibrium with the corpuscles in their midst, the temperature must be that which corresponds to the average kinetic energy of the latter; so we see how it is that the temperature is gradually raised down the rod. Of course, the molecules themselves also play a part in this "diffusion of heat"; but it is small compared with the influence of the free corpuscles, owing to the relatively high velocity of the latter. Further, if we can express mathematically the rate of distribution of the kinetic energy along the rod, we can state all the laws of heat-conductivity. There will evidently be differences in different metals depending upon their various physical constants; and it is possible to deduce the formulæ in terms of quantities which have well-known physical meanings.

The conduction of an electrical current by a metal consists essentially in the actual transport of the corpuscles along the conductor.

The condition required to produce a current is that there should be maintained an electric force in a conductor. We picture the corpuscles as attached for a while to the molecules, then existing free from them, then attached again, etc. During the intervals of freedom the corpuscles will drift under the influence of the impressed electric force, thus constituting the current. The intensity of the current will depend upon the distance the corpuscles are moved under the electric force; and this obviously is conditioned among other things by the interval of time in which the corpuscles are free to move. The formula for the conductivity in terms of the same physical constants as used in the one for heat-conductivity can be calculated.

We thus see that both kinds of conductivity owe their mechanism to the presence of corpuscles; and Drude, Thomson, and Lorentz have all calculated the various quantities connected with heat- and electrical conductivity which admit of experimental determination; and, although the agreement between theory

and fact is not as good as desired, nevertheless it is sufficiently satisfactory to confirm our belief in the essential features of the theory. (When the number of free corpuscles for any one metal is calculated, as it can be approximately, it is found to be different for different metals; it appears to be true that each molecule furnishes a small number. The total number, however, is so large that a serious difficulty enters when we consider certain other heat properties of the metals.)

The corpuscular theory of a metal and the assumption of the connection between temperature and the kinetic energy of the corpuscles have received most wonderful confirmation by the experiments[1] of Professor Richardson, of Princeton University. It has been known for many years that hot metals had interesting electrical properties, and within a comparatively recent period it has been shown that these were due to the emission from the surface of the metals of numbers of corpuscles.

[1] *Phil. Mag.*, 1908–12. He gives a summary of his work in *Proc. Amer. Phil. Soc.*, vol. I, p. 347 (1911).

Granting the presence of the corpuscles moving to and fro between the molecules, it is an obvious consequence that some of them should escape from the surface. At any one instant a certain proportion of the corpuscles will have a certain velocity; and, if the total number of corpuscles is very great, we can apply the theory of probabilities — just as Maxwell did to the molecules of a gas — and thus can calculate the relative number of corpuscles having various stated velocities at any one temperature of the metal. This Richardson has done; and, further, by measuring the velocity of the corpuscles as they escape from the surface and the relative numbers having different velocities, he has shown an excellent agreement between the two sets of figures, calculated and observed. Few investigations of recent years have been as admirable in all respects as this one of Richardson's; it combines in a most happy manner keen mathematical ability in stating the physical hypotheses and great experimental skill in testing the formulæ obtained; and, when discrepancies have arisen

between the facts of experiment and predictions from theory, the modification in the hypotheses which he has made have been most suggestive in other fields.

Richardson calls the free corpuscles in a metal "thermions" and the branch of physics concerned with the observations of their properties "thermionics." The importance of the subject seems to justify the creation of the new names, because the spontaneous emission of these corpuscles by metal molecules is just as universal a property as is the emission of radiant energy. No theory of thermal or electrical properties of matter can be considered which is not based upon these two characteristic emissions.

An interesting illustration of the emission of corpuscles by a hot body is furnished by the sun. There can be no doubt but that it is ejecting these in enormous quantities; and we can best account for certain terrestrial phenomena by assuming that some of these corpuscles from the sun ultimately reach the earth's atmosphere.

Another property of matter which is explained on the theory of the existence of corpuscles is what has been called the photo-electric effect. Many metals which at ordinary temperatures emit comparatively few corpuscles lose them in large numbers if light falls upon the surface; and many if not all non-conductors do the same. Whatever concept we may have of the nature of radiant energy, it is a fact that it consists of a certain condition which exerts a force upon any electric charge. The radiation is produced by oscillations of charges, and when it falls upon a charge it exerts a force upon it. Thus, as the radiant energy from the sun or from an arc light or a spark falls upon a body, the corpuscles in the latter will be given additional motion; and, if the velocity attained is sufficient, they will be able to escape from the surface. The experimental investigation of this photo-electric effect has been one of the most interesting of recent years; and there still remain many points which require further study. All experiments go to prove that these ejected corpuscles are

not "free" ones, but those forming part of molecules.

Owing to the accelerations of the free corpuscles in metals there is, of course, an emission of radiant energy. Some of this emerges into the space outside the body, giving rise to the characteristic continuous spectrum of a solid body; but part of this energy emitted by any one corpuscle is also received by other corpuscles. So the effect of this internal radiation is the same as that of energy penetrating from without; and we might expect therefore that part of the spontaneous emission of corpuscles by metals is in reality due to an internal photo-electric action.

We get evidence of photo-electric action of another kind in the action of light upon selenium. This substance has most interesting chemical and physical properties, and is known to exist in several forms, the molecular groupings of which are not yet clearly understood. In one of these forms it is a very poor electric conductor; but, if light falls upon it, its conducting properties are increased. The explana-

tion of this phenomenon, which has been offered by Dr. A. H. Pfund[1] and which is most satisfactory, is that the radiation penetrating into the selenium ionizes the molecules, causing the emission of corpuscles which have all the properties of free ones so long as the light is being absorbed.

The most obvious difference between a conductor and a non-conductor lies in the fact that, for all general purposes, a solid conductor is opaque to light, while a non-conductor is transparent. Of course, neither statement is absolutely correct; if a piece of metal, e.g., gold, is beaten out into a thin film, it is transparent to greenish-blue light; ordinary glass is absolutely opaque to certain light-waves; sulphur and pitch are opaque to ordinary light. But on the whole, the distinction is a good one; and all metals are absolutely opaque to all types of light unless they are made in extremely thin films. The reason is not far to seek. When radiant energy falls upon a metal, the free corpuscles are given additional motion;

[1] *Phys. Rev.*, vol. XXVIII, p. 324 (1909).

this requires work; and consequently the amount of radiant energy which penetrates into the metal is continuously decreased.[1] It is evident that this is true for radiant energy of every kind. But in addition to the free corpuscles, all metals have, of course, the corpuscles which form part of the atoms in the molecules. These we may call "bound"; and, whatever is our conception of the structure of the atom, we picture these bound corpuscles as capable of emitting radiation having definite periodicities, characteristic of the kind of matter. Then, as the radiant energy which we call light falls upon the molecules in the outer surface of the metal, these bound corpuscles will be given additional energy, by a process of resonance; and, if they remove a large amount of energy from the incident radiation, the latter will penetrate only a short distance into the metal. Similarly, non-conductors are made up of molecules which contain bound corpuscles — practically no others; but there is this essential difference between the two

[1] See Wood, *Physical Optics*, new edition, 1911.

bodies, conductors and non-conductors: in the former the bound corpuscles can escape with comparative ease, as is shown by the properties we have been discussing; in the latter, they cannot escape except under most strenuous conditions. Speaking in a general manner, this means then that the bound corpuscles of a metal can be moved much more easily than those of a non-conductor; and therefore in the case of the former the incident radiant energy will be taken up by a very thin layer of molecules, while in a non-conductor a much greater thickness is required. Further, owing to the difference in the extent to which the bound corpuscles respond in the two cases, and since this absorption must be a resonance process, there will be absorption by the non-conductor only if the incident radiant energy contains periodicities equal to those of the bound corpuscles. In other words, the non-conductor absorbs only in a "selective" manner, while the conductor absorbs all radiation; but its selective action is so intense that it takes place in the "skin" only. Owing to this fact, that

practically all of the absorption of the radiant energy by the bound corpuscles of a conductor takes place in a layer containing only a few molecules, the added motion of these corpuscles will all be practically identical; and therefore their combined motion will give rise to a reflected disturbance of the period characteristic of them. Radiant energy of a definite period produces a definite color-sensation, provided the period lies within certain limits; and thus we see why it is that metals have characteristic colors, which are marked by a great intensity. On the other hand, when radiant energy penetrates a non-conductor and is absorbed, a thick layer of molecules is required; and therefore there is not any agreement in the nature of the vibrations of the corpuscles at different depths; consequently they cannot react together and produce an emergent reflected disturbance — some of the corpuscles will be vibrating in one direction, others in the opposite, etc. (This condition is not unlike the state of affairs if a pendulum is struck a number of random blows from all directions, and as a

consequence there is no resultant motion.) The energy absorbed by the corpuscles of a non-conductor, in general, ultimately becomes distributed among the molecules, and is shown by a rise of temperature or some other heat-effect.

I have spoken of non-conductors as if they were composed entirely of neutral molecules; but the fact should be noted that when the temperature is sufficiently high, many non-conductors are able to conduct electric currents.

The corpuscular theory of metals which I have given is not the only one which can be devised to account for the experimental facts; and, in fact, Thomson has developed a theory along other lines, which in its deductions is free from some of the objections raised against the simpler theory. It is most probable that the complete theory of the properties of a metal will require us to take into account not alone the free corpuscles but also the bound ones inside the molecules; it would be very remarkable if this were not so.

There are many other properties of metals, as distinct from non-conductors, which have been discovered from time to time and have been investigated by many people. Chief of these are the various phenomena of thermo-electricity and those associated with the Hall effect. These are described in full in the more modern textbooks of physics; and Thomson and Richardson have shown how the main phenomena can be deduced as consequences of the corpuscular theory. There are great difficulties it is true; but still every one believes that the great conception of free corpuscles will serve as a basis for the complete explanation of all metallic phenomena.

This lecture cannot be concluded without saying a few words about magnetism. A piece of matter is called a "magnet" if it has the power to attract iron — excluding, of course, any such action due to gravitation or electrification. Some ores as found in mines are magnets; but most of us are accustomed to see magnets in the form of steel bars or lozenge-shaped "needles." Such a magnet has the

power to attract not only iron but nickel, cobalt, and a few other substances, all of which are called "magnetic." The subject of magnetism has been for centuries the object of scientific investigations; and at the present time we know many facts of great importance concerning its manifestations. One of these is that each minute part of a magnetic substance is itself a magnet, with its north and south "poles," and that by no means in our control are we able to separate the two poles. In short, we seem to be justified in saying that each molecule of a magnetic substance is a magnet itself. In this connection Professor Weiss of Paris has made a most important discovery.[1] He has shown that the magnetic strengths of the elementary magnets of all the magnetic substances are multiples of the same quantity. That is, calling the ultimate magnet a "magneton," the elementary magnet of one substance may be equivalent to two magnetons, that of another to ten, etc.

The fact which demands explanation, how-

[1] *Journal de Physique* (v), vol. I, pp. 900, 965 (1911).

ever, is the existence of the magneton, or, if this investigation of Weiss's is not considered conclusive, the existence of any elementary or molecular magnet. Ampère showed, nearly one hundred years ago, that, if there were an electric current flowing in a molecule, the latter would have the properties required for magnetism ; but this simply states the problem in a different manner. This point of view has, however, one great advantage when we consider molecules and atoms as containing corpuscles ; because, if there are inside the atoms corpuscles or rings of corpuscles in rapid rotation, this condition is in all respects equivalent to an electric current. Bearing this fact in mind, Langevin[1] and others have developed theories of magnetism which are to a certain extent satisfactory. There are, however, great difficulties which are not yet entirely overcome. One is the fact that there is a well-known alloy of copper, aluminium and manganese — all non-magnetic elements — which is itself markedly magnetic.

[1] *Ann. Chem. et Phys.*, Ser. VIII, vol. V, p. 70 (1905).

VI

MODELS OF ATOMS; CONCLUSIONS

Let us, as an introduction to this the concluding lecture, summarize what we have learned in the preceding lectures, so as to see to what point our theory and our knowledge of experiments have brought us.

We have discussed the mass and weight of matter, the emission of radiant energy by all bodies, the subdivision of matter into molecules and atoms and the converse processes — the combination of atoms to form molecules, and the grouping of molecules to form extended bodies, and the general subdivision of all bodies into conductors and non-conductors; we have shown that part at least of the mass of a body may be attributed to the existence of positive and negative charges in the atoms, which we proved were present; we have offered as an explanation of gravitation a certain law of force between these electric charges in

the atoms; we have shown how radiant energy is due to acceleration of corpuscles; and finally we have explained radio-activity, chemical combinations, and the distinctive properties of conductors as due to certain stable and unstable arrangements of corpuscles in combination with the corresponding positive charge.

What remains to be done, therefore, is to devise a model of corpuscles and positive charge which will have the requisite properties of stability and of variability required for the different assumptions made, and will in addition offer the possibility of explanation of the periodicity which atoms of different elements show, as was stated in the first lecture. The only one who has attacked this problem with any success is Thomson. In the "Philosophical Magazine" of March, 1904, he published his epoch-making article on this subject. Since then he has not seriously modified his fundamental idea; and but few additions worthy of note have been made by others.[1]

Bearing in mind the fact that negative

[1] See the references on p. 214.

charges always occur in the form of corpuscles and that no smaller positive charge than the hydrogen atom has ever been obtained, Thomson proposed as the fundamental structure of all atoms a comparatively large positive nucleus consisting of a sphere in which positive electricity is uniformly distributed and inside of which are placed the corpuscles, arranged in such a geometrical configuration as to make the entire atom stable.

For simplicity of mathematical treatment Thomson assumed that the corpuscles were arranged at equal intervals around the circumferences of circles, all of these having as a common centre that of the sphere and all lying in one plane. Thus a certain number of corpuscles lie in one circle of a comparatively small radius, distributed at equal intervals; a certain number lie in a different circle outside the first one, and also equally distributed, although the interval between them need not be the same as in the former circle, etc.

We see, then, that the corpuscles constituting any ring are repelled outward, away

from the centre, by their mutual interaction, since they are all charged alike; but the action of the positive electrification is to draw them in the opposite direction, back towards the centre. Consequently, if they are in equilibrium, these two forces must balance each other. This is of course true if we assume the ring of corpuscles to be at rest; but, if it is rotating in its own plane, so that each corpuscle is moving in a circle, an additional force is required, directed towards the centre — just as the force of gravitation acting on the moon is required to make it move in a circle around the earth. Consequently, in this case of rotation the arrangement of the corpuscles must be such that the attraction due to the positive electrification exceeds the repulsion owing to the interaction of the corpuscles themselves by an amount sufficient to maintain the rotation.

This particular model of an atom was selected by Thomson only because of the ease with which the mathematical difficulties could be solved. As he says, the object is to show

that stable arrangements of corpuscles will have many properties in common with real atoms and this special case is chosen solely on the ground of simplicity. "The number of corpuscles corresponding to any particular property would doubtless be different if we took a three- instead of a two-dimensional distribution of corpuscles, or if instead of supposing the attractive force exerted by the positive electricity to vary directly as the distance from a fixed point we assumed that the density of the positive electricity inside the sphere was not uniform."

In making his actual calculations for the possible configuration of circular rings of corpuscles Thomson assumed that these were at rest; but in discussing the properties of these atomic models he showed how it was necessary to assume rotations in order to secure stability and also to illustrate the properties of actual atoms. If a definite rotation is required for stability, we can easily understand that, if owing to radiation of energy, the velocity of this rotation decreases, the force of attrac-

tion towards the centre may be sufficient to cause an internal explosion.

The simplest type of atom would be one in which there was a single corpuscle placed at the centre of the atom; and the next simplest that in which all the corpuscles are in one ring; and Thomson investigated mathematically the conditions of stability when there were two, three, etc., corpuscles in the ring. He showed that, as the number was increased, there came a time when the criterion of stability required that the last corpuscle added be placed at the centre of the sphere rather than in the original ring; and that, as two, three, etc., more were added, the condition of stability required these to be arranged in an inner concentric circle. Thus, if the number of corpuscles is very large, the most stable arrangement would be one in which there are several such rings. Of course, in working out these distributions of corpuscles due attention was paid to the need of having the quantity of positive charge equal to that of the total negative charge for any definite number of corpuscles.

It is evident that, if we work out the stable configurations for one, two, three, etc., up to a large number of corpuscles, there will be shown a definite periodicity. Thus, consider an atom containing simply a ring with three corpuscles; there will be another atom containing three corpuscles in an inner ring and additional ones in an outer ring; there will also be another containing still added corpuscles in a second outer ring, etc. In this way we see how it is possible to account for different atoms and also for the periodicities which we have shown exist between atoms of different elements. Thus, the following is an illustration of the stable arrangements found starting with a nucleus of a ring of five corpuscles: (*a*) five corpuscles in a ring; (*b*) five in an inner ring, eleven in an outer; (*c*) five in one ring, eleven in one outside this, fifteen in the outmost; (*d*) five in one ring, eleven in the next, fifteen in the next, seventeen in the outmost; (*e*) the same as the preceding with an outer ring of twenty-one added, etc. It is very evident that we have here a periodicity; and if any definite

physical property is characteristic of a ring of five corpuscles, this will appear in all the atoms mentioned — modified, of course, by the presence of the other rings. There are similar groups of atoms having as a nucleus a ring of four corpuscles, etc. Such a group of atoms all having the same inmost circle of corpuscles corresponds to a "column" in the periodic system of the atoms of the elements. Any one interested in the numerical distribution of corpuscles in rings can find all the facts given in Thomson's writings.

Thomson also investigated in this connection a problem which in some respects is more important than the fundamental one just discussed. That was this: Given a neutral atom consisting of the positive sphere and the associated rings of corpuscles, will the system still be stable if a corpuscle is added or removed? — and by how much relatively is the potential energy of the system changed by either of these steps? This problem we see is different from the preceding one, because in this the atom, modified by the addition or removal of

a corpuscle, is no longer electrically neutral; and it evidently is fundamental in discussing the explanation of the formation of molecules.

With the assumptions made as to the arrangement of the corpuscles in circles, Thomson found that the simplest atom would be one having a single corpuscle at the centre, the next simplest then would have two corpuscles in a ring, the next three, etc.; up to an atom having five corpuscles in a single ring; then, if there are six corpuscles, the theory demands five corpuscles in a ring and one at the centre, etc. When the number of corpuscles is large, so that there are several rings, there will be several atoms all of which have the same number of corpuscles in the outmost ring. Thus the nine atoms having from fifty-nine to sixty-seven corpuscles all have twenty in the outer circle. These nine atoms we can call a "row." Thomson showed that the atom at the left-hand end, having fifty-nine corpuscles, is comparatively unstable and can easily lose a corpuscle, but that, if it does so, it will

owing to its positive charge attract to itself another corpuscle, and so return to its previous condition. On the other hand, if a corpuscle is added to this atom, it is stable; similarly, if two, three, etc., up to eight corpuscles are added. Thus, this atom would be considered as electro-positive, having a valency of zero; but in a molecule where it is combined with an atom more electro-positive than itself it might reach a valency of eight. The atom, having sixty corpuscles, can, under the disturbing influence of other charged atoms, lose one corpuscle and still be stable; but if it loses two, it will attract back one; thus it is electro-positive and has a valency one; it is possible for it to be stable also if we add to it one or more, up to seven, corpuscles; thus it is possible for it to have a valency seven in certain molecules. Similarly, the atom having sixty-one corpuscles is more stable than the two before it, but under disturbing actions it may lose two corpuscles; and, if it does, it will still be stable; it is, therefore, electro-positive and has a valency of two. Considering the

atoms at the other end of the row, the one having sixty-seven corpuscles is extremely stable, so that corpuscles could be removed only with difficulty; but it would be possible for it to lose one, two, etc., up to eight, and still be stable; and, if a corpuscle were to be added, it would not keep it. Therefore, as an electro-positive atom it would have a valency of eight, and as an electro-negative one, a valency of zero. The atom before it, having sixty-six corpuscles, would, if any opportunity offered, attach a single corpuscle and would then be very stable; but the addition of two would make it unstable; therefore, it would be an electro-negative atom having a valency one. It could, however, be made to lose one, two, etc., up to seven, corpuscles, and would still be stable; thus, in a molecule with an atom more electro-negative, it might have a valency seven, etc.

The same facts appear in regard to the atoms in any one row. Let us now compare them with the actual chemical atoms. Two of the rows of the periodic table are: —

(1) Helium — Lithium — Beryllium — Boron — Carbon — Nitrogen — Oxygen — Fluorine — Neon.
(2) Neon—Sodium—Magnesium—Aluminium—Silicon — Phosphorus — Sulphur — Chlorine — Argon.

At the left-hand ends, Helium and Neon have a valency zero; Lithium and Sodium are strongly electro-positive and have a valency one; Beryllium and Magnesium are also electro-positive and have a valency two, etc. At the other end, Neon and Argon have a valency zero; Fluorine and Chlorine are strongly electro-negative with a valency one, etc. Iodine, which comes in the same column as Fluorine and Chlorine, is electro-negative with a valency one, as in the molecule hydriodic acid, HI; but when combined with Chlorine, an atom more electro-negative than itself, it has a valency five, as shown in the molecule ICl_5.

We thus see how wonderfully Thomson's model of atoms allows one to explain the fact that some atoms are electro-positive and others electro-negative and also the existence of valency. It is specially interesting to note also that the fact of an atom having different val-

encies in different types of molecules is explained. Thomson showed also that his model of an atom would explain many other well-known facts of chemistry, notably the properties of unsaturated compounds and of those compounds of Carbon which show asymmetry. When we consider the simplicity of the assumptions, the agreement between their consequences and the phenomena of Chemistry is such as to lend strong support to the corpuscular theory of matter.

We can also obtain a general impression as to the essential difference between a metal and a non-metal, as shown by the facts of electrical conductivity, the emission of corpuscles, etc. All metals would correspond to those types of Thomson's atoms which can lose corpuscles with comparative ease; so that in a collection of molecules made up of such atoms there might well be what may be called an evaporation of corpuscles into the intramolecular spaces. We should then have these free corpuscles, in addition to the bound ones inside the atoms.

The process by which a radio-active atom

loses corpuscles and alpha particles must undoubtedly be more of an explosive nature than is this spontaneous emission of corpuscles inside metals. This has been explained as due to the loss of energy of the ring of corpuscles and its consequent decrease in velocity of rotation. If this is great enough the atom may become unstable; because, if the velocity of revolution of the corpuscles becomes too small, the electric forces will disrupt the ring; then owing to this instability there would be a rearrangement of parts inside the atom; and, if the process is sufficiently violent, parts of the atom may be ejected. By an internal change like this we can account for the emission of both alpha and beta particles; and the evidence is fairly conclusive that the gamma rays are in general a consequence of the emission of the corpuscles which constitute the beta particles. This explanation of the transformation of a radio-active atom cannot, however, be regarded as satisfactory; because this change is independent of the age of the atom, and obeys simply the law of probability.

The question as to whether the positive electrification of the atom is distributed uniformly or gathered in particles has been raised; but the experiments[1] of J. R. Crowther on the transmission of Roentgen radiation through various substances seem to prove that it is uniform.

Of course, as Thomson made clear in his first paper, one must not attach too much importance to the simple hypothesis made as to the distribution of the corpuscles; many other stable configurations can be imagined.

Quite recently[2] a modification of Thomson's hypothesis has been made by H. A. Wilson. He considers each corpuscle as being electrically saturated by the positive electrification in a small sphere at the centre of which is the corpuscle, so that each of these spheres is elec-

[1] *Proc. Roy. Soc.*, vol. LXXXIV, p. 226 (1911). See also two papers by Rutherford, *Phil. Mag.*, vol. XXI, p. 669 (1911); vol. XXIV, p. 453 (1912). Nagaoka, in the *Phil. Mag.*, vol. VII, p. 445 (1904), discussed the stability of an atom consisting of a minute positive nucleus surrounded by rings of corpuscles.

[2] *Proc. Amer. Phil. Soc.*, vol. I, p. 366 (1911). *Phil. Mag.*, vol. XXI, p. 718 (1911).

trically neutral. Thus the problem becomes a geometrical one of dividing the large atomic sphere into a number of equal volumes equal to the number of corpuscles, each small volume being as nearly spherical as possible. Taking the elements in any one column of the periodic system, he considers that each atom is formed from the one before it by the addition of a spherical layer containing a whole number of the small equal elements of volume. Thus, beginning with different nuclei, different atoms can be built up; and, assuming that the mass of an atom is proportional to the number of corpuscles, we can develop the theory. On comparing this with the relative masses of the chemical atoms a very remarkable agreement is found; and a most interesting consequence is that the actual number of corpuscles in a hydrogen atom is eight; and the number in other atoms is therefore known.

Let us now see how far the Thomson atom does explain the properties of matter. The main facts of chemistry are accounted for in an admirable manner; so are those concerned

with metals; and mass and gravitational forces follow naturally. The most important fact not yet specifically discussed is the emission of radiant energy. If we picture this as due to the periodic motions of the bound corpuscles in the atoms, grave difficulties arise, some of which have been mentioned in a previous lecture. There is, however, a great deal of evidence to support the belief that radiant energy is emitted only when what we call chemical action is going on; that is, molecules are forming or are being dissociated into atoms. If this is true in all cases, the Thomson atom also accounts for the facts. Chemical action consists in a rearrangement of corpuscles to form attracting doublets, or in the passage of corpuscles from one atom to another; this is accompanied of course by great accelerations, specially at the beginning of the motion of transition and at the end; and acceleration of a corpuscle, as we have seen, is a requisite for the emission of radiant energy. Again, the whole system of corpuscles in any molecule will have a certain average acceleration which is periodic, and

different molecular groupings of the same atoms will have different periodicities. In a previous lecture this matter has been discussed at some length; and the important facts brought out were that the "molecular vibrations" might give rise to the isolated lines of a discontinuous spectrum; and the accelerations of the individual corpuscles as they leave and join atoms would cause pulses of radiant energy which combine to form a continuous spectrum.

The conclusion of this whole discussion, then, is this: If we assume that we can apply to the minute structure of an atom the general laws of dynamics and of electricity which our experiments on material bodies and on actual charged bodies and electric currents lead us to accept, we can account for the general phenomena of matter by considering it made up of atoms, each consisting of a spherical nucleus of positive electrification and groups of corpuscles. This hypothesis has the great advantage of being so concrete that it has suggested and will continue to suggest

numerous lines of experimental investigation, all leading to the discovery of new facts.

When we come, however, to a more careful consideration of the phenomena of radiant energy, that is, to the question as to the type of disturbance which gives rise to this energy and to the effect produced upon matter by the reception of this energy, our present theory seems to fail. This points to the possibility that we must make other assumptions in regard to the connection between radiant energy and an electric charge. Whatever assumptions are made in the future, they must, however, be of such a nature as to leave undisturbed the facts to which I have called your attention in these lectures. We may obtain a new series of equations for dynamics and electricity; but they cannot differ sufficiently from those we have used to lead to consequences essentially different from those which follow from our present equations, when these are tested by the observed properties of ordinary material bodies or by ordinary electric phenomena. In other words, a continuous increase in knowl-

edge, not an overthrow of past achievements, is to be expected.

The latter half of this lecture I wish to devote to a discussion of the method followed in the preceding lectures, and, in so doing, to describe briefly the attitude of physicists to-day towards the interpretation of natural phenomena. As was said in the first lecture, the general line of progress is: first, observation; second, working hypothesis; third, further experimental investigation. The value of a good hypothesis consists, to a large degree, in the stimulation it gives to new experiments; for, whether the hypothesis is verified or not, the facts as found by the experiments remain, they are permanent and of ever-enduring usefulness.

Since man is limited in the formation of mental pictures to actual experiences or to extensions of them, and since his attention is first called to physical phenomena by his senses, it is most natural that, when he becomes conscious of phenomena to which his senses do not respond, he should attempt to devise a mechanical model, i.e., a material mechanism

consisting of pulleys, levers, wheels, cords, etc., which should have properties as nearly as possible like the phenomena concerned. Lord Kelvin[1] went so far as to say that he did not understand any particular point in physics unless he was able to construct a mechanical model of it. Thus, in studying the properties of matter, the early students of physics pictured it as capable of subdivision into minute parts called molecules, each of these being essentially like the whole body. Thus undoubtedly a molecule is pictured by most people as a minute heavy sphere. Of course, they had no evidence of the existence of a single concrete particle; it was too small to see or to weigh. Many phenomena referring to matter had been observed; some of these were capable of mathematical expression; what these physicists did was to convince themselves that, if there were minute particles of matter endowed with certain properties, the phenomena observed with actual bodies were logical consequences of the assumptions made with

[1] S. P. Thompson, *Life of Lord Kelvin*, vol. II, p. 830.

reference to the molecules. This process does not constitute a proof of the existence of molecules. In order to demonstrate this, we must first prove that no other assumptions will lead to the same phenomena. The difficulty of this is easily understood. Therefore, we can appreciate the point of view of a philosopher who says that he does not care to go back of the observed phenomena and their statement in concise laws, but prefers to stand upon these last as his ultimate knowledge. As a matter of fact, Lord Kelvin had moments of uncertainty, even towards the end of his noble career, as to the reality of molecules as particles of matter. Sir J. J. Thomson told me that once, when Kelvin and Stokes were accompanying him through his laboratory, Kelvin said to them that he had his doubts about the molecular nature of matter, and Stokes stopped short in their progress and gave what Thomson said was the most concise and convincing argument in regard to the molecular constitution of matter that he had ever heard. Kelvin acknowledged himself fully

satisfied. To one who knew the two men, Kelvin and Stokes, the greatest men of their day in the whole realm of physical science, the incident is thoroughly characteristic of their qualities. As a matter of fact, it is doubtful if we have any right to say that there ever was a proof of the existence of molecules, as ordinarily conceived, until the experiments of Rutherford and Geiger upon the emission of alpha particles by radium, to which reference has been made in a previous lecture.

Again, consider the varied phenomena which we associate with the word "electricity." Clerk Maxwell succeeded in a brilliant manner in expressing by a series of beautiful equations all the experimental facts discovered by Faraday, Cavendish, and the long line of investigators. His concepts were two kinds of matter, conductors and non-conductors, each having definite electric properties to which numbers could be given, and a universal medium capable of transmitting electric and magnetic forces, called the æther. The equations themselves have been most aptly called

"Maxwell's Theory" of electricity; but many eminent scientists were not content until they had devised mechanical models, which gave motions satisfying mathematical laws identical in form with some of Maxwell's. As more electrical phenomena were discovered, notably the Zeeman effect, it was necessary to modify Maxwell's equations, in order to embrace the new facts; and this was most satisfactorily done by H. A. Lorentz, of Leyden. In the interpretation of his equations Lorentz used the concepts of a space occupied by a medium incapable of translation and of a number of minute electric charges called "electrons" which are distributed through this medium. These electrons are thought of as being in general grouped in definite geometrical volumes, which we call material bodies; and the differences between conductors and non-conductors are made to lie in the mode of grouping and in the forces acting in the different groups. (It is evident, of course, that the theory is not based entirely upon known laws of forces between charges, but assumes the

existence of other forces not yet capable of explanation.) The essential difference between Maxwell's and Lorentz's theories lies in the treatment by Maxwell of a material body, such as a piece of glass, as a body by itself, having its own distinctive properties; while Lorentz considers it simply as a geometrical figure in a stationary medium, occupied by discrete electric charges. It is evident that Thomson's concept of an atomic negative corpuscle and an equal positive charge of larger volume can be at once introduced, if desired, into Lorentz's equations; so of course can many other concepts. The equations themselves make up what we may call our definite knowledge; the interpretation of them depends upon the individual point of view. It should be noted, however, that, although both Maxwell's and Lorentz's equations are stated in terms of electric and magnetic forces, quantities whose variations can be noted by changes in bodies which are apparent to our senses, — i.e., quantities which may be measured by physical instruments, — to Maxwell and to his immediate

followers attention was concentrated upon matter as such, while to Lorentz and to scientists to-day all thought is centred upon electric charges. Many men have tried and many are still trying to picture a mechanism, purely material in its concept, which has the properties of an electric charge; that is, they attempt to assign such mechanical properties as mass, elasticity, etc., to a medium and to design such models as will exhibit phenomena capable of expression in mathematical laws identical with those applicable to electric charges. At the present day, however, such attempts have in the main ceased; and most people are content with postulating the existence of electric charges as such. This does not mean in the least that this is to be the final stage of our interpretation of nature; the whole history of the development of science is absolutely opposed to such a thought.

As a further illustration of the main idea which I am trying to emphasize, let me mention the concept of radiant energy, which I have already described in the course of these lectures.

It was a direct consequence of Maxwell's equations that energy emitted into the æther by oscillations of the electric and magnetic forces would be propagated with a definite velocity which was identified with the so-called "velocity of light." The same is true, of course, of Lorentz's equations, which are simply extensions of Maxwell's. To Maxwell, however, this oscillation of the electric and magnetic forces was due primarily to a motion of a charge on the surface of a conductor or to the variation of a current in a conductor, i.e., the electric charge and the current were treated separately. Lorentz, on the other hand, thinks of a real acceleration in space of an electrical charge as being the cause of the radiation.

The mechanism of the propagation does not enter into either theory. Before anything could be said on the subject, it would be necessary to describe the properties of the æther in terms of the characteristics of matter. Thomson showed mathematically, however, many years ago that it was possible to picture the process of radiation as the advance through the æther of tubes

of electric force. These are drawn differently from the ones of which I have spoken in the preceding lectures. According to the view adopted by Thomson within recent years, each corpuscle has permanently attached to it certain radial tubes; in the older, classical method, a line of force at any point of space has the direction of the resultant force at that point due to all the charges acting, positive and negative; so there is an imaginary geometrical line of force at *every* point of the electric field. In general, of course, as there are always equal amounts of positive and negative charges, lines of force will always begin on one and end on the other. But Thomson and also Hertz showed that in the case of electric oscillations, — such as are used, for instance, in wireless telegraphy, — tubes of force, as thus defined, exist in the æther, forming closed curves, and that these tubes travel with the velocity of light. By attributing a real existence to these moving tubes, Thomson explained in an exceedingly simple manner many of the phenomena of electricity and light.

Maxwell's equations and theory say nothing explicitly in regard to the way radiation is produced; Lorentz, on the other hand, predicates an electron having an acceleration. In this last case, the electron will carry with it in its motion its electric field; but outside this, at a distance from the electron which is large compared with its dimensions, there will be a "radiation field," consisting of outspreading spherical waves. In neither theory is there any condition making it necessary for the wave-front to be continuous; both theories state that at any point in the æther where the electric force has a value the conditions are such as correspond to the advance along a certain line of the disturbance existing there. The geometrical surface perpendicular to these lines we may call the wave-front. However, there is no reason on either of the two theories why the electric force should *not* have a value at *all* points of space, which would, therefore, require a continuous wave-front.

Thomson was the first, as has been said, to advance the idea that an electric charge does

not produce a continuous field of force; and his scheme for securing such a condition is to make the hypothesis that a corpuscle possesses a limited number of permanently attached radial tubes which are capable of propagating a transverse disturbance. This is an addition to Lorentz's theory, inasmuch as the action of the electric force is limited to certain lines; i.e., at all points off these lines we must equate the force to zero. With this modification, we may apply Lorentz's equations and draw all the conclusions which he and others have done.

Within a very recent time a distinctly new idea has been brought forward by Planck in the treatment of the emission of radiant energy. We have seen that the three fundamental elementary entities in terms of which we aim to explain physical nature are corpuscles, atoms, and energy. We can reduce the consideration of all charges and all matter to ultimate parts; all corpuscles are alike; the atoms of any one element are identically alike so far as there is any evidence. Planck suggested that, in a similar manner, radiant energy consists of

ultimate parts, those emitted by any one type of atom being identically alike. This is a most startling suggestion at first sight, and was not at first received with great favor, although, as Thomson has shown, it is a consequence of the fact that a definite amount of energy is required to drive a corpuscle out of any molecule.

In Planck's theory, the source of radiation is a definite type of electric oscillator; and by making certain assumptions, concerning the plausibility and meaning of which there has been considerable dispute, he arrives at the conclusion that there is an elementary quantity or "quantum" of radiant energy, characteristic of each oscillator, or "radiator," as he prefers to call it. Thus each radiator emits only whole numbers of these quanta. However, when such a radiator absorbs energy, it does so by a continuous process. The numerous difficulties in Planck's theory have been well brought out by Professor Wien, of the University of Würtzburg, in his article on "Theory of Radiation" in the "Encyclopædia

of the Mathematical Sciences."[1] Planck was able, however, by his assumptions to deduce a formula which expresses in a most satisfactory manner the facts of the radiation by "black bodies," and also, by comparing his formulæ with known facts, to deduce values for the elementary atomic charge, the number of molecules in a given volume of a gas, etc., all of which agree well with those obtained by more direct means.[2]

Taking Newton's equations as typical of our theories of mechanics and Maxwell's as typical of our electrical theories, it is important to realize that the test of their usefulness primarily is their statement of the facts of nature as we observe them. We are living on the earth, a body each point of which is moving rapidly in space; further, our instruments

[1] See also Poincaré, *Journal de Physique* (v), vol. II, pp. 5, 347 (1912).

[2] For an interesting description of the "quantum" theories of radiation, see an article by Millikan in *Science*, January, 1913. There is an intimate connection between this hypothesis of Planck and the general theory of equipartition of energy in all forms, as is shown by recent work on specific heats.

allow us to measure only those quantities which are of limited dimensions. What equations would hold if the earth were at rest in space, granting that the idea is conceivable, or what are the properties of extremely minute quantities or very large ones, or of bodies moving with great velocities, etc., we have no way of knowing. We can *assume*, of course, that the equations which we have apply to quantities of all dimensions, large and small; and we can use ordinary mathematical processes to extend our equations to the relative motion of bodies with reference to a frame of reference fixed in space. This is, as a matter of fact, what has been done by Lorentz, Thomson, and others; and the results of this method are those which I have given in these lectures. Even in the adoption of this procedure certain modifications have to be made in Newton's laws of motion. In these laws Newton included only the mass of material bodies; but, by the application of Maxwell's equations, it soon became evident that radiant energy also possessed mass, and so Newton's laws as origi-

nally stated are not in accord with facts. Thus, a source of light owing to its radiation experiences a reaction; and when the radiation falls upon any body it is pushed in the direction of the beam of light. Of course, this effect is extremely minute and requires special apparatus for its detection. Again, difficulties enter when we attempt to define what is meant by equal intervals of time or by equal lengths or by saying that two events on different bodies, e.g., the sun and the earth, occur simultaneously.

Our only justification in the method we have followed in using and extending our equations comes from the fact that the consequences deduced have been reasonable and consistent with each other. We must also bear in mind that we might equally well have adopted equations which differed extremely little from our accepted ones; and we would have no way of deciding between the two if we applied them to ordinary phenomena. If by the extension of our fundamental equations we are led to any deduction which is contrary

to fact, it shows that our hypotheses are wrong; if we are led to deductions which seem improbable, — a very dubious expression, — we might be tempted to make an entirely new start, make new hypotheses, and develop a new mathematical analysis. This condition has arisen. In speaking of the rapid motion of material bodies through space, I called your attention to the fact that a logical consequence of Lorentz's theory is the change of dimensions of the moving body, a contraction in the line of motion. This seemed to some people to be a conclusion which was what I may call artificial; and in any case the equations developed by Lorentz to apply to rapidly moving bodies were of extraordinary complexity.

As a consequence of these and other facts, Professor Einstein, of the University of Prague, has developed an entirely new philosophy of natural phenomena. He begins by making several fundamental assumptions, one of which is that all phenomena are electrical in their origin, and draws the consequences by rigid mathematical steps. The hypotheses

which he makes are not sufficient to permit the deduction of all the equations we need for a complete theory of nature; but, so far as the development has been carried, the results are most satisfactory. It may be of interest to note a few of the statements of the theory; there is no universal medium such as a stationary æther; the idea of giving a number to a length is a matter of definition; whenever the velocity of light enters into an equation, it has the properties of a number infinitely large, that is, adding to it or subtracting from it a finite number leaves it unaltered; if one body is moving with reference to another with a velocity v_1, and the second is moving with reference to a third with a velocity v_2, the velocity of the first with reference to the third is not the sum of v_1 and v_2, as it is in the ordinary mechanics of Newton (but the results are the same, provided the two numbers are small). Einstein's point of view towards nature is more that of what is called a philosopher than of an investigator. His hypotheses are not suggested directly by our sense-

experiences, but are statements which seem reasonable; but their sole justification, from a physical sense, will rest in their deductions being in accord with observations. In Newton's and Maxwell's hypotheses, the experimental observations came first, and directly suggested the mathematical assumptions. The conclusion drawn by Jeans and others from the recent experimental work on radiant energy and specific heats of solid bodies is that the facts of nature cannot be deduced from differential equations — which assume continuity in space and time.

That modern science is built on a sure foundation no one can doubt; from the publication of Newton's "Principia" to the present day, the progress has been continuous. Each year our vision is broader, and the explanation lies in the fact that our understanding of the minute phenomena of nature is clearer. No one conception has been so inspiring and so suggestive as that of Thomson as to the corpuscular structure of matter; and no mathematical discussion has been so luminous as that of

Lorentz of the properties of corpuscles or electrons. Whatever wealth of knowledge the future has in store for us relating to the connection between corpuscles, atoms, and energy, no names will stand out more clearly in the history of thought in the twentieth century than those of Joseph John Thomson and Heindrik Antoon Lorentz.

THE END

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